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## *Volume II—User's Manual*

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David E. Edwards, and Anton J. Landgrebe

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# An Analysis for High Speed Propeller-Nacelle Aerodynamic Performance Prediction

## *Volume II—User's Manual*

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# SUMMARY

A user's manual for the computer program developed for the prediction of propeller-nacelle performance reported in Volume I, "An Analysis for High Speed Propeller-Nacelle Aerodynamic Performance Prediction - Theory and Initial Application" is presented. The manual describes the computer program mode of operation requirements, input structure, input data requirements and the program output. In addition, it provides the user with documentation of the internal program structure and software used in the computer program as it relates to the theory presented in Volume I. Sample input data setups are provided along with selected printout of the program output for one of the sample setups.

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# INTRODUCTION

The purpose of this manual is to provide the user with sufficient documentation to run the computer code for the propeller-nacelle performance analysis (PANPER) developed by the United Technologies Research Center (UTRC) under contract to the NASA Lewis Research Center. The computer analysis is capable of predicting the performance for high speed propeller-nacelle configurations for either single or coaxial counter-rotating propellers for either an internal flow condition (wind tunnel) or external flow conditions (free flight). The analysis was developed by combining and modifying existing propeller performance prediction capabilities applicable to the high speed flight problem with an existing axisymmetric through flow analysis modified to calculate external flow problems. The resulting combined analysis couples the separate solution procedures by including in each solution portion in a consistent manner the appropriate effects due to the respective portions of the two solution procedures. The basic program structure is shown in the flow diagram of figure 1. The propeller performance solution is obtained including the influence of the nacelle body, and the flow field and nacelle performance are calculated including the influence of the work done by the propeller on the fluid. Either of the performance solutions (propeller or nacelle) can be obtained without the other if so desired. The technical aspects of the solution procedure are detailed in reference (1) and will not be explained here. This manual has been written under the assumption that the reader has read the technical report (reference 1) and is familiar with the theoretical features of the analysis.

This manual consists of two major portions: 1) a description of the setup and input data required to run the computer code; and 2) documentation of the internal program software as it relates to the technical aspects of the analysis.

The input portion is broken into three sections, describing the basic program setup requirements and program mode operation, the propeller related setup and input and the nacelle related setup and input, in this order. The documentation portion consists of two sections which describe the subroutines and labeled common blocks used in the computer program for the propeller and nacelle portions of the analysis, respectively.

# DESCRIPTION OF THE PROGRAM OPERATION

This section is intended to describe the general features, program setup and input data of the PANPER computer program in sufficient detail so that the program can be operated successfully by the user. Input to this program consists of three parts; the program mode control data, propeller data and nacelle data, in this order. The input data for each of these parts will be described in the following subsections.

The first subsection describes the various modes that the program will operate in and the input control switches. Special attention should be paid to these mode switches since this program may in effect solve one of three problems:

(1) Propeller Lifting Line Analysis only
(2) Nacelle Analysis only
(3) Combined Propeller-Nacelle Analysis

The second and third subsections present a detailed description of the input, output and diagnostics of the Propeller Lifting Line Analysis and Nacelle Analysis portions of the program, respectively.

The computer program was written and developed in FORTRAN V Computer Language for use on a UNIVAC 1110 computer. Before execution of the PANPER Program, fourteen files must be assigned in the JCL RUNSTREAM. Information about these files is given in Table (I). Sample Runstreams for three cases are presented in Appendix A, and selected output for the second case is presented in Appendix B.

TABLE I

PANPER FILE ASSIGNMENTS

| Unit No. | Array Name | Length (WDS) | No Block | Subroutine | Purpose | Program Mode |
|---|---|---|---|---|---|---|
| NDRUM=8 | F(NEQ,3,IST) | LNGT3=3,000 | IS=100 | SOLVI | Store viscous solution | NOPPF=0,1 |
| JDRUM=9 | Q(19,IST) | ISL=1900 | IS=100 | COORST | Store duct geometry | NOPPF=0,1 |
| CDRUM=10 | FF(7,2,IST) | IFFS=3400 | IROW=10 | FORCE | Store blade forces | NOPPF=0,1 |
| LDRUM=11 | AFF(LNGT2) | LNGT2=6600 | IST/30+1 | SOLVI | Store matrix coef. | NOPPF=0,1 |
| IWAKE=12 | | | | | | |
| JDBLD=13 | See BLDOUT | 556 | IROW=10 | BLDOUT | Store lifting line geometry dimensionless | NOPPF=0,1 |
| NCALV=14 | CINP(4,IST) | LCALV=400 | IS=100 | CALINV | Store inviscid solution | NOPPF=0,1 |
| JDBLDD=16 | See BLDOUT | 556 | IROW=10 | BLDOUT | Store lifting line geometry dimensional | NOPPF=0,1 |
| 20 | See WAKCOR | 300 | IROW-2 | WAKCOR | Wake displacement effect | NOPPF=-1,1 |
| 1 | GCDIMZ,GCDIMT,GCDIMR | 180 | 180 | SETMAT | Lifting line geometry influence coefficient | NOPPF=-1,1 |
| 2 | GCDIMZ,GCDIMT,GCDIMR | 180 | 180 | SETMAT | Lifting line geometry influence coefficient | NOPPF=-1,1 |
| 3 | GCDIMZ,GCDIMT,GCDIMR | 180 | 180 | SETMAT | Lifting line geometry influence coefficient | NOPPF=-1,1 |
| 4 | GCDIMZ,GCDIMT,GCDIMR | 180 | 180 | SETMAT | Lifting line geometry influence coefficient | NOPPF=-1,1 |
| 30 | See REDMAT | 360 | 360 | REDMAT | Save matrix coefficient lifting line | NOPPF=-1,1 |

## Input Mode Control

This subsection describes the mode control input data card required to operate the PANPER Program. Information from this card will determine which mode of operation the PANPER Program will perform in. On this card the Mode of operation control information is read in as described below:

| Name | Column | Format | Comments |
|---|---|---|---|
| NØPPF | 1-2 | I2 | NØPPF = -1, The propeller analysis is performed without including the nacelle effects calculated directly from the nacelle portion of the program. NØPPF = 0, The nacelle analysis is performed uncoupled from the propeller lifting line code. The blade forces may be considered through input. NØPPF = 1, The propeller and nacelle analysis is performed through coupling of the nacelle portion and the propeller lifting line portion of the code. |
| NØPPC | 2-4 | I2 | Indicates number of passes through the viscous flow algorithm of the nacelle portion and the propeller portion. See reference 1, Section entitled: Description of the Combined Analysis Solution Procedure. |

It should be observed that for NØPPF = 0, the propeller data will not be read in and for NØPPF = 1, the nacelle data will not be read in. Descriptions of the propeller and nacelle data are given in the following subsections of this section. Samples of this card can be seen in Appendix A. Finally, it must be noted that NØPPC is a cycle counter on the number of passes through the viscous propeller-nacelle flow solution. It may be desirable to cycle through the viscous flow solution and propeller solution until the propeller blade forces do not significantly change. However, experience to date has not demonstrated a necessity to perform this cycle for propeller performance applications.

## Propeller Portion

### Major Input Features

The major input features consist of four basic groups of input data along with the appropriate program control data. These four groups of data are blade geometry, airfoil characteristics, inflow properties and the wake geometry. In the following subsections, these groups of input are described in some detail so that the user will understand their importance.

#### Blade Lifting Line Geometry

The geometric description of the blade lifting line representation of the blade is of primary importance for obtaining the most accurate solutions given the assumptions inherent in the analysis. The hub-pitch axis centered cartesian coordinates for each lifting line segment boundary must be input (XSB, YSB, ZSB) consistent with the input blade twist distribution (THET) so that the program can correctly rotate this geometry about the pitch axis for the required blade angle. The coordinates for the definition of the blade tip for the tip Mach cone calculations (XMC, YMC, ZMC) must also be input consistent with the twist distribution. For counter rotating coaxial propellers, each set of coordinates is input referenced to its respective hub and pitch axis centers. The technical description of this coordinate system is detailed in reference 1, see figure 2. The selection of the blade segmentation is of primary importance in regions of severe loading gradients. For these regions (generally the tip of the blade) finer segmentation is required as compared with regions of weak gradients.

#### Propeller Blade Airfoil Characteristics

To calculate the blade airloading, it is necessary to specify the distribution of airfoil type along the blade radius. There are three different sets of airfoil data available in this analysis: two sets of NACA 16 series isolated airfoil data, whose characteristics are described in reference 1, and one cascade airfoil data set for NACA 65 series, also described in the above noted reference. The user specifies the use of these airfoil data sets by specifying the radial location which denotes the outer boundary of the region (RADCAS) for which it is desired to use the cascade data set. Outboard of this region, the distribution of the identification number (23 or 24) for the isolated airfoil data sets is input through the airfoil type designation number distribution input (AIRN). If desired, it is possible to model the cascade effects on the isolated airfoil data by application of an analytical cascade correction (CASCAD). This model is also described in reference 1. The use of this model may be desirable for two reasons: first, if the inboard section of the propeller blades is not adequately modeled with NACA 65 series airfoil sections, and second, if the cascade influence extends beyond the region where the NACA 65 series airfoil types apply.

Once the distribution of airfoil type and cascade regions are determined for the design under consideration, the particular airfoil characteristics are defined by additional input. These characteristics are: the design lift coefficient (DECL), the thickness to chord ratio (TØVC), and the chord (CØRD).

## Inflow Properties at the Blade Row

This analysis allows the user the ability to describe the noninduced inflow properties at the propeller blade rows if run independent from the nacelle portion of the analysis. It is therefore possible to prescribe the nacelle's influence (or any desired influence) on the inflow conditions at the propeller blades without running the nacelle portion of the analysis. This may be desirable if the variation of the nacelle's influence is small for slight changes in the propeller designs. The inflow properties are the axial (VØVO) and radial (URVO) noninduced inflow velocity ratio distributions, and the density (DENS) and speed of sound (SØUN) ratio distributions along the blade radius. These distributions scale the respective freestream values to define the local inflow conditions at the blade rows.

## Wake Model Description

The description of an accurate wake geometry for the flight condition under investigation is of primary importance for accurate predictions of the induced inflow solution and the resulting propeller blade air loading. The wake models available have been described in detail in the technical section of reference 1; however, a brief review of the applicable wake models for the different flight regions follows.

For static thrust conditions, the generalized wake model should be used (figure 3). It has been clearly demonstrated to be the most accurate model available and is necessary for accurate performance solutions. Wake rollup modeling must also be used for this flight condition (figure 4). In low speed flight conditions, the classical (figure 3) or modified classical wake model (standard model for high speed flights) is probably sufficient for reasonable performance predictions; however, it is clear that the wake model must have some of the features of the generalized wake model (radial contraction, in particular). Because of this, it is possible to use the generalized wake model for nonzero flight speed conditions. In this case the generalized wake model will have the inflow velocity distribution superimposed on it to describe the wake geometry. Thus, with careful selection of the input generalized wake coefficients, it is possible to model a low speed wake geometry if the required characteristics are known. Wake rollup modeling should probably be used for these flight conditions. For high speed flight conditions, the wake is carried away from the propeller so rapidly that it is doubtful that any model other than the classical or modified classical wake will be required. Generally no wake rollup modeling is required at these flight speeds.

Similar considerations must be given to the influence of the nacelle on the wake geometry. For static thrust conditions, the nacelle influence cannot be modeled by using the nacelle portion of the analysis. However, if the displacement of the wake due to the presence of the nacelle is known, it can be modeled through the wake geometry input option. For all other flight conditions, the nacelle's influence can be included directly in the analysis.

If it is desired for any reason to use a wake model which is not geometrically compatible with the basic wake models available, the wake geometry can be input in cylindrical coordinate form. This allows for a wide range of possible wake modeling capabilities in this analysis.

## Detailed Description of Propeller Data Input and Setup

### Standard Input Data and Setup

The propeller input data is grouped into 3 distinct data sets, the first set consists of input data which describes the propeller analysis modeling options, freestream flight conditions and primary propeller characteristics. The second set of data defines the physical location of the blade lifting line segment boundaries and the coordination used to define the location of the tip Mach cone. These items are referenced to their respective centers of rotation. The third set of data is used to describe the local blade element flight inflow properties (based on the freestream flight condition) and secondary blade characteristics. This data set consists of interpolation tables for the required items. All of these input data sets are described in the following subsections. For coaxial propellers, the second and third data sets are repeated for the second propeller following all of the data sets for the first propeller. Two sample propeller input data decks are listed in Appendix A (case 1 and case 3) for an isolated propeller mode and a combined coaxial propeller-nacelle mode. Each data set is initiated by a header card with an alphanumeric label in card columns 1 through 6 (left justified) and terminated by a card with the alphanumeric label END in card columns 1 through 3. Within a given data set, there is no ordering dependency for the input items and if duplicity of the item occurs, the last value read will be used. All numbers are input in FORTRAN floating point or exponential format.

### Data Set I

The header card for this data set consists of the characters INPUT in card columns 1 through 5. The input data required for this data set is input one card at a time following the header card. Each card has a label and value punched on it. The label designates the item and the value for that item follows the label on the card. The label is an alphanumeric, three to six character name, left justified in card columns 1 through 6, with the input value following in a FORTRAN E20.8 format (columns 7 through 26). The description of the labels and corresponding input data items are listed below. For items with the numeric characters 1 or 2 on the end of the label, the 1 and 2 designate the first and second propeller quantities respectively for a coaxial condition. If the input item is omitted, a value of 0.0 is used internally.

| Input Label | Description |
|---|---|
| BLADE1,BLADE2 | Blade number per propeller |
| CASCAD | Option switch to use an analytical cascade correction on isolated airfoil data, a value of 1.0 requests the model based on flat plate theory, a value of 2.0 uses a model based on empirical correlations of reference 44 in Volume I. |

| Input Label | Description |
|---|---|
| CBWAKE | Option control for including the effects of compressibility on the induced velocity calculation from the bound lifting line vortex (this model is of questionable validity). A value of 1.0 sets this option, a value of 2.0 sets this option but the bound influence on the blade generating the effect is neglected. Should use 0.0. |
| CNSECT | Fraction of the chord measured from the leading edge, used to determine the tip Mach cone intersection location on the blade for the Evvard tip correction, generally the trailing edge (1.0) is used. A zero input sets this value to 1.0. |
| CØFLØW | Option control for overriding the limitation that the wake and bound vortex compressibility effects be applied only when the section Mach numbers are greater than 1.0. (This model is of questionable validity.) An input value of 1.0 engages this option. Should use 0.0, see section entitled: Compressibility Considerations for Induced Velocity, of reference 1. |
| CØMPRS | Option control for including the effects of compressibility on the induced velocity calculation from the trailing wake geometry. A value of 1.0 sets this option. This option should be used. |
| CPI | Requested power coefficient for performance iteration. A zero value assumes no iteration. This iteration option will not work for coaxial propellers. |
| CTI | Requested thrust coefficient for performance iteration. A zero value assumes no iteration. This iteration option will not work for coaxial propellers. The power iteration will override this option if both are requested. |
| DCPDT | The derivative of power coefficient with respect to blade angle. If the power coefficient iteration is requested and this value is nonzero, the input value is used to determine the second iteration blade angle value, otherwise a change of 1.5 degrees in blade angle is used for the second iteration. |

| Input Label | Description |
|---|---|
| DCTDT | The derivative of thrust coefficient with respect to blade angle. If the thrust coefficient iteration is requested and this value is nonzero, the input value is used to determine the second iteration blade angle value, otherwise a change of 1.5 degrees in blade angle is used for the second iteration. |
| DEBUG | Intermediate print option control, generally not used (0.0). A value of 1.0 requests printout of many quantities associated with the geometry transformations, geometric influence coefficients, circulation matrix and intermediate aerodynamic quantities. A value of 2.0 requests a full debug printout and should not be used. |
| DENSTY | Freestream air density (slugs/ft$^3$) |
| DFRNAC | Input skin friction drag ($lb_f$) due to the nacelle. Included in the performance calculation if input A positive value is opposite the direction of positive thrust. |
| DPRNAC | Input pressure drag (lbf) due to the nacelle. Included in the performance calculation if input. A positive value is opposite the direction of positive thrust. |
| DPSI | Maximum size of the azimuth increment (degrees) allowed to define the wake geometry and azimuthal interval in either single or coaxial mode. The program internally calculates the actual value. |
| EVAARD | Option switch to request tip relief model. An input value of 1.0 requests tabled values for the Evvard model be used, a value of 2.0 requests that a functional form for the Evvard model be used which is slightly different than the tabled values, a value of 3.0 requests that conical flow theory be used with a variable Mach number distribution, while a value of 4.0 uses a fixed Mach number. |
| G400 | Option switch to couple via an external file to an aeroelastic response analysis. If nonzero, the value identifies the device unit number to be used. |

| Input Label | Description |
|---|---|
| HUBQ1, HUBQ2 | Input hub torque (ft-$lb_f$). This input value will be included in the performance calculations and performance iteration loops. A positive value represents a power loss which the engine must overcome. However, the fluid does not sense this loss. |
| PRINTI | Option to delete vector input listing, nonzero to perform this function. |
| PRMAT | Geometric Influence Coefficient print option, generally not used (0.0). A value of 1.0 requests the printout of the geometric influence coefficients used to compute the induced velocity in both the cylindrical coordinate system and the blade element coordinate system. |
| PRNTØP | Option to delete performance printout of spanwise distribution quantities, nonzero to perform this function. |
| PRØPT | Wake geometry print option, generally not used (0.0). A value of 1.0 requests that the wake coordinates be printed. |
| PRØPNM | Number of propeller blade rows (1 or 2). |
| RAD1, RAD2 | Input blade radius (along the pitch axis), this value may not be the true radius if the blade is swept off of the pitch axis (ft). |
| RDCAS1, RDCAS2 | Outermost fraction of the blade radius for which the cascade airfoil data will be applied. If zero no cascade airfoil data is used. |
| RDTRN1, RDTRN2 | Maximum radius to which the airfoil transition interpolation model can be applied. This value is also the flag which requests this option. |
| REV | Number of revolutions of wake geometry used to model the actual wake. The value chosen should be sufficient in length to approximately model an infinite wake's influence. Low flight speeds require a larger number of revolutions of wake geometry than high speed conditions. For high speed conditions use 2.0. |

| Input Label | Description |
|---|---|
| RØLUP1, RØLUP2 | Option switch to model trailing wake rollup. A nonzero value requests that the input value represents the number of outer filaments to be rolled up into the tip vortex filament at a specified azimuth position behind the blade. When this model is requested, the remaining filaments are implicitly rolled up into a remaining or root vortex. See figure 4. The value to use should correspond to the maximum circulation location. |
| RPMRF1, RPMRF2 | Reference rpm for twist increment due to steady airloads. |
| RPM1, RPM2 | Propeller rotation speed (rpm). |
| SKINØP | Option switch which requests a skewed flow drag model. An input value of 1.0 requests this option. |
| SØUND | Freestream speed of sound (fps). |
| STACK | Fraction of chord measured from the leading edge to define the position of the lifting line on each blade element, generally the quarter chord line is used (0.25). |
| STN | Number of inflow stations per blade. Maximum of 15. Generally at least 10 are used. |
| TAUEXP | Exponent for airfoil transition interpolation function. |
| THETA1, THETA2 | Input reference blade angle (degrees). This reference angle rotates the input twist distribution about the pitch axis. If the performance iteration is requested this value will be changed internally and the input value is the first iteration value. Positive leading edge up. |

| Input Label | Description |
|---|---|
| TRUCI1, TRUCI2 | Azimuth position behind the blades for which the root rollup occurs, a zero value assumes rollup starts immediately at the blade. Because there is generally no root vortex formed, a large value should be input when rollup is requested (degrees). |
| TRUCT1, TRUCT2 | Azimuth position behind the blades for which the tip rollup occurs, a zero input assumes rollup starts immediately at the blades (degrees). |
| TYPCAS | Option switch to select cascade type. An input of 0.0 requests no cascade data be used. A value of 1.0 uses the correlation from reference __, while a value of 2.0 requests the correlation of reference ___. |
| VIMØM1, VIMØM2 | Input momentum induced velocity, used to define the wake geometry. If a performance iteration is requested, this value is internally corrected to match the resultant performance (fps). |
| VKTAS | Freestream flight velocity (knots). |
| VØRCØR | Fraction of the blade radius to define a vortex core for geometric influence coefficient calculations. Generally 10 percent of the chord is used. |
| WAKEØP | Option control for wake model selection. A zero value requests the standard wake model (modified classical wake) defined by the momentum-induced velocity and the radially varying input axial inflow velocity distribution be used. A value of 1.0 requests a wake model defined by the flight velocity and momentum input velocity be used (classical wake). A value of 2.0 requests that the wake geometry be input to the analysis and a value of 3.0 requests that the wake coefficients for the generalized wake model be input. |
| WAKNAC | Option control for including the effects of the nacelle on the wake geometry through the use of a displacement correction to the requested wake model. The option generally requires that WAKEØP = 1.0 so that double accounting of the nacelle's influence on the wake geometry does not occur. An input value of |

| Input Label | Description |
|---|---|
| | 1.0 requests this option. If the standard wake model (WAKEØP = 0.0) is requested with this option, the program execution will be terminated because of this double accounting of the nacelle's influence. If it is actually desired to use the standard wake model, this feature can be overridden by adding to the program input, immediately following the input data, a card with the alphanumeric characters ØVER in card columns 1 to 4. |
| ZHUB | Nondimensional (radius of propeller one) displacement between the propeller disc centers for coaxial propellers. A positive value places the second propeller behind the first. Must be consistent with input for nacelle portion of the analysis. |

Data Set II

The header card label for this data set is BLADE, in card columns 1 through 5. The first input after the header card must be the integer value for the number of blade segment boundaries, free field format. Following this input card, the data items are input. For each set of blade segment boundary items (STN+1), a labeled header card is input with the alphanumeric labels described below, followed by the free field formatted vector* (root to tip) on the next card for the item in question. For the tip Mach cone definition quantities, this format is identical but the vector item is replaced by a single value. All of these items should be input.

| Input Label | Description |
|---|---|
| XSB | Input cartesian coordinate vector, X, inboard to outboard, to define the blade lifting line segment boundaries. Nondimensionalized by the blade segment radius boundary value (RAD1). Maximum of 16 boundaries (15 segments). |
| YSB | Input cartesian coordinate, Y, to define the blade lifting line segment boundaries, nondimensionalized by the last segment boundary value (RAD1). Maximum of 16 boundaries (15 segments). |

* Free field format consists of a series of numbers (Fortran floating point or exponential) separated by commas. If more than 80 card columns are needed for an input vector, the vector continues on the following card.

| Input Label | Description |
|---|---|
| ZSB | Input cartesian coordinate, Z, to define the blade lifting line segment boundaries. Nondimensionalized by the last segment boundary value (RAD1). Maximum of 16 boundaries (15 segments). |
| XMC | Input cartesian coordinate, X, to define the blade leading edge tip location for the tip Mach cone definition. Nondimensionalized as noted above. |
| YMC | Input cartesian coordinate, Y, to define the blade tip location for the tip Mach cone definition. Nondimensionalized as noted above. |
| ZMC | Input cartesian coordinate, Z, to define the blade tip location for the tip Mach cone definition. Nondimensionalized as noted above. |

Data Set III

The header card for this data set is labeled VARDAT. The input interpolation tables for each item in this data set are input with a header card with the label for the particular item on it, followed on the next card by the integer number of interpolation stations in free field format (minimum of 4, maximum of 20). The independent vector (non-dimensional X-wise coordinate) for the particular item follows on the next card (root to tip) in free field format. The dependent vector values then start on a new card following the independent vector in the corresponding order. An example of the format for one input item follows:

| | Format |
|---|---|
| Label | (Alphanumeric) |
| N | (Integer) |
| $X_1, X_2, X_3, \ldots, X_n$ | (Floating Point) |
| $Y_1, Y_2, Y_3, \ldots, Y_n$ | (Floating Point) |

The required input items are described below.

| Input Label | Description |
|---|---|
| AIRN | Airfoil type designation number distribution. There are only two values for input, 23.0 which requests the Manoni airfoil data tables and 24.0 which requests the NACA airfoil data tables (reference 1). Because the values used internally are computed by interpolation from this input vector and then converted to integer values, the input values of 23.1 and 24.1 are generally used to guarantee that the integer values of 23 and 24 are used internally. These values start at the hub even if the cascade data is used. |
| CØRD | Chord distribution in feet. |
| THET | Built in blade twist distribution in degrees. Leading edge up (direction of positive rotation) is positive. |
| DECL | Design lift coefficient distribution. |
| TØVC | Airfoil thickness to chord ratio distribution. |
| DENS | Local blade row density to freestream density ratio distribution. Overridden if Nacelle portion of the analysis is used. |
| SØUN | Local blade row to freestream speed of sound ratio distribution. Overridden if Nacelle portion of the analysis is used. |
| URVO | Local blade row radial inflow velocity to freestream velocity ratio distribution. Overridden if Nacelle portion of the analysis is used. |
| VØVO | Local blade row axial inflow velocity to freestream velocity ratio distribution. Overridden if Nacelle portion of the analysis is used. |
| BETA | Dynamic twist distribution, internally scaled by the ratio of rpm to reference rpm squared. Incrementally added to static twist distribution, degrees. |

## Optional Generalized Wake Geometry Input Coefficients (WAKEØP = 3.0)

In order to maintain flexibility with regard to the generalized wake model, the generalized wake geometry equations are included in a separate subroutine which requires the input of a set of generalized wake coefficients if this model is requested. In this subroutine the input wake parameters are applied to the wake equations to compute the wake filament coordinates. The input instructions for the wake geometry subroutine (RWZW7) are included herein.

The wake equations for the generalized wake model, containing the input generalized wake coefficients, and graphs showing the applicable wake regions of the equations are presented in figure 5 (in which program symbols are used). The designations r = 0 and r = 1 indicate nondimensional radial coordinates at the axis of rotation and at a distance of one propeller radius from the axis of rotation, respectively. The wake representation is also explained in reference 2; however, for the wake equations therein: (1) AK30 and AK31 are not included, (2) it is assumed that AK10 is zero and (3) the axial coordinate for the tip vortex and the vortex sheet extension to r = 1 is relative to the blade tip instead of the propeller hub.

## Input for Generalized Wake Geometry

| Card No. | Column | Program Symbol | Description of Input Item |
|---|---|---|---|
| 1 | 9-10 | IØPT | Option for the vortex sheet boundary within a wake azimuth of 360./BL and the blade (fixed point, right adjusted). Normally, set IØPT = 1 to establish a parabolic vortex sheet boundary through: (1) the origin of the outermost vortex sheet filament at the blade, (2) the rolled up tip filament coordinates at an azimuth of 360./BL and (3) the intersection of the vortex sheet at an azimuth of 360./BL and the tip vortex boundary. IF IØPT = 0, a linear vortex sheet boundary is established between (1) and (3) above. See reference 2 for more detail. |
| | 11-20 | A | Curve fit constant, A, in the tip vortex radial coordinate equation (see figure 5). |
| | 21-30 | LAMBDA | Curve fit constant, LAMBDA, in the tip vortex radial coordinate equation (see figure 5). |

| Card No. | Column | Program Symbol | Description of Input Item |
|---|---|---|---|
| | 31-40 | PHINPO | Wake aximuth angle, PHINPO, that separates the axial velocity regions AK20 and AK30 for the vortex sheet extension to r = 0, degrees (see figure 5). |
| | 41-50 | PHINP1 | Wake azimuth angle, PHINP1, that separates the axial velocity regions AK21 and AK31 for the vortex sheet extension r = 1, degrees (see figure 5). |
| 2 | 1-10 | AK1T | Axial velocity of the tip vortex between the blade and the passage of the following blade at wake azimuth 360./BL (nondimensionalized by rotor tip speed; negative down). |
| | 11-20 | AK2T | Axial velocity of the tip vortex after the passage of the following blade at the wake azimuth 360./BL (nondimensionalized by rotor tip speed; negative down). |
| | 21-30 | AK10 | Axial velocity of the vortex sheet extension to the center of rotation in the wake azimuth region between the blade and the passage of the following blade at the wake azimuth 360./BL (nondimensionalized by rotor tip speed; negative down). |
| | 31-40 | AK20 | Axial velocity of the vortex sheet extension to the center of rotation in the wake azimuth region between the passage of the following blade at the wake azimuth 360./BL and the wake azimuth PHINPO (nondimensionalized by tip speed; negative down). |
| | 41-50 | AK30 | Axial velocity of the vortex sheet extension to the center of rotation following the wake azimuth PHINPO (nondimensionalized by tip speed; negative down). |
| | 51-60 | AK11 | Axial velocity of the vortex sheet extension to r = 1 in the wake azimuth region between the blade and the passage of the following blade at the wake azimuth 360./BL (nondimensionalized by rotor tip speed; negative down). |

| Card No. | Column | Program Symbol | Description of Input Item |
|---|---|---|---|
| | 61-70 | AK21 | Axial velocity of the vortex sheet extension to r = 1 in the wake azimuth region between the passage of the following blade at the wake azimuth 360./BL and the wake azimuth PHINP1 (nondimensionalized by tip speed; negative down). |
| | 71-80 | AK31 | Axial velocity of the vortex sheet extension to r = 1 following the wake azimuth PHINP1 (nondimensionalized by tip speed; negative down). |

Optional Input Wake Geometry (WAKEØP = 2.0)

If desired, an arbitrary wake geometry model may be used in the analysis by input of the complete wake geometry. The only constraints for the wake model are that the description of the geometry is assumed identical for each blade (a required assumption in the solution procedure) and that the coordinates be input in the cylindrical coordinate system for equally spaced wake azimuth positions consistent with the blade azimuth increment and inflow station boundaries. This model allows for the most exact description of the wake geometry, if known, given the inherent assumptions of the analysis. The description of the input format follows.

The wake geometry is input in separate sets for each trailing wake filament, inboard to outboard. Each set contains subsets for each revolution of wake geometry requested. Each subset will start with a new card. The radial and axial coordinates are paired (radial, axial) for the trailing wake segment boundary for each wake azimuth position (wake age) starting at the youngest and ending with the oldest wake segment boundary. Thus, the wake azimuth position is implicitly assumed to be consistent with the input blade azimuth (DPSI) increment and the number of trailing segments must be constant with the number of wake revolutions. The FORTRAN format used is 10F8.4 for each card of data. There are KTØT (number of trailing filament) sets of cards. Each set of cards contains NTØT (number of wake revolutions) subsets, with each subset containing JTØT1 (number of wake azimuth positions per revolution + 1) pairs of wake coordinates. Because each subset of data will contain a complete definition of a revolution of wake geometry, the first coordinate pair of each subset will be identical to the last coordinate pair of the previous revolution, excepting the first subset. The total number of input data pairs is then (KTØT)x(NTØT)x(JTØT1). For a typical high speed condition using two revolutions of wake, 12 segment boundaries and a blade azimuth increment of 15 degrees, the number of pairs would be (12)x(2)x(25) = 600 or 1200 single values.

## Description of Propeller Solution Output

The propeller output section can be broken into three distinct portions, initial, intermediate and final output. The program user has a large number of print options which control the amount of intermediate output. The initial and final output are not optional. The descriptions of the output quantities are presented in the following sections. A sample printout for selected portions of the propeller solution portion is presented in Appendix B. It should be noted that in the description to follow there is only one propeller and propeller position for a single propeller configuration. For coaxial propellers the intermediate output is repeated for each propeller.

### Initial Output

During the reading of the propeller input data, the data as read in is immediately printed out. This information is entitled: PRINTOUT OF INITIAL DATA AS READ IN, and if the program execution terminates during the reading of an input data item, the user will see the item which was last read before program termination. This feature has two advantages: first, if an incorrect item is attempted to be read in, the user can quickly determine the incorrect item; and second, a complete listing of the propeller input data as used in the analysis is available for later review if desired. This output section always occurs during the input of the propeller data. If the combined analysis (propeller and nacelle) mode is being used, this output occurs long before (precedes the nacelle inviscid solution) the other portions of the propeller output. This feature can be partially suppressed if desired by the input control, PRINTI. This option will suppress the vector printout quantities if requested.

The next output for this initial output is a section entitled: PROGRAM INPUT SUMMARY, and consists of the input data displayed in a structured format. The propeller modeling options used for the particular execution are listed in the following form. The integer value of the input modeling option is displayed with a brief description of the model used. The freestream conditions are listed next, (VKTAS, SØUND, DENSTY) followed by the propeller operating characteristics (PRØPNM, BLADEN, RPM, ZHUB). The parameters which define the wake and blade geometry segmentation are displayed next (STN, STACK, DPSI, REV, CNSECT) followed by the propeller characteristics (RAD1, HUBQ1, THETA1, RDCAS1, VIMØM1) of each propeller. The printout of the propeller characteristics includes: the blade lifting line segment boundaries coordinates (XSB, YSB, ZSB, BETA); the inflow station coordinates and the blade properties at the segment centers as interpolated from the input distributions (AIRN, CØRD, THET, DECL, TØVC, VØVO, URVO, SØUN, DENS).

Intermediate

The intermediate output is described below. Generally it is limited to the minimum amount possible since most of the output is repeated in the final output section. The intermediate output is repeated for each iteration in blade angle. If there is no performance iteration it is printed only once for the input blade angle. This output is entitled: PROGRAM OUTPUT FOR PROPELLER PERFORMANCE ITERATION NUMBER X.

The first output data for this section is not optional; it consists of a table of the blade lifting line segment center and boundary coordinates for the reference blade angle and the blade angle value in degrees. The coordinates are listed in cartesian and cylindrical form for the centers and boundaries. Following this table, the coordinates for the definition of the tip Mach cone location are listed in cartesian form for the blade angle in question. If no optional printouts are requested, the wake transport velocity distribution is printed as a function of blade radial location. If optional printouts are requested this print does not follow immediately, but occurs later in the output. All other output for the intermediate portion is optional. The input option controls (in parentheses) and the respective descriptions of the output follow (output labels in parentheses if not noted).

The output of the trailing wake geometry coordinates (PRØPT) is presented in the cylindrical coordinate system and tabulated as a function of wake azimuth position and blade radial position. This output is entitled: WAKE COORDINATES. The radial coordinates are tabulated first, starting with the values at the blade and ending with the oldest element. A table of the axial coordinates is then presented in the same format.

The printout (PRMAT) of the summed geometric influence coefficients for each inflow station at each propeller position for each propeller as a function of the appropriate inflow station and propeller position of each propeller is presented in the cylindrical coordinate system and in the blade element coordinate system. This printout is entitled: CYLINDRICAL GEOMETRIC INFLUENCE COEFFICIENTS or BLADE ELEMENT GEOMETRIC INFLUENCE COEFFICIENTS. The propeller and propeller position indices are so noted on the printout, while the inflow station indices are not, since the values are presented for the inboard station to the outboard station for each propeller and propeller position.

For detailed intermediate output (DEBUG) the following extensive list of items is presented in the same format as noted above for the propeller, propeller position and inflow station indices. Generally this printout should not be used. A section of detailed blade element properties consisting of the magnitude (if it applies) and unit vector direction cosines in the cylindrical coordinate system is output for each of the following: the blade segment lifting (SB, ALSRAD, ALSPHI, ALSAXL), input chord (CINPUT, ALCIRD, ALCIPH, ALCIAX), the normalwise unit vector (ALNRAD, ALNPHI, ALNAXL), the blade element chord nondimensionalized by blade radius (CHØRD, ALCRAD, ALCPHI, ALCAXL), input blade element thickness to chord ratio (TØVERC, ALTIRD, ALTIPH, ALTIAX), the blade element thickness to chord ratio magnitude only (THK) and the blade element design lift coefficient (DESCLP). This section is entitled: DETAILED BLADE ELEMENT ØUPUT. The next section consists of detailed blade element velocities and unit vector direction cosines (VTØT, ALVRAD, ALVPHI, ALVAXL) in the cylindrical coordinate system along with the direction cosines in the blade element coordinate system (VS, VC, VN) and the angle of attack (ALPHAN), and inplane aerodynamic skew angle (SKEW), all computed without including the propeller induced velocities, entitled: DETAILED VELOCITY RELATED OUTPUT (EXCLUDING INDUCED VELOCITY TERMS). The indices associated with the internal program "DO LOOPS" for the geometric influence calculations are then output, along with the cosine and sine functions for the respective inflow stations inplane lag angle and propeller azimuth position and a counter rotation flag with each line of output marked: INTERMEDIATE OUTPUT. Following this output, the normalwise blade element geometric influence coefficients are printed in the circulation matrix form for each propeller at each propeller position for each inflow station. The title of the output is: GEOMETRIC INFLUENCE COEFFICIENT. Following this output some untitled cascade related items are listed. The chord-to-gap ratios (TAU) and gap-to-chord ratios (SIGMA) are listed along with the geometric angle between the propeller direction of rotation and the local blade element chordwise vector (THETAG) which represents the compliment of the cascade stagger angle. Tip Mach cone quantities (untitled) are then output. The Mach cone angle is listed and then the angle between the blade tip and the location of the specified fraction of the blade chord for each inflow station is listed. The tip Mach number value is listed next. The station location index (NSTAT) for the intersection of the Mach cone and the fraction of the blade chord is listed and the resulting Evaard Tip Relief correction factor (XKCØNE) for each blade inflow station is presented. The blade element Mach number (SMACH) and the total Mach number (CMACH) distributions are listed along with the blade element geometric angle of attack (excluding induced terms) distribution in radians (ALPHA). Following this output, the linearized lift curve slope (AA), an aerodynamic quantity ($D = \frac{8\ R}{ac}$), the matrix cønstant vector (CØNST) and the blade element geometric blade angle (THETA) in degrees are listed. The induced velocity component distributions (VIN, VIC, VIS) in the blade element coordinate system at each inflow station of each propeller for each propeller position are presented due to each propeller, followed by the total of both propellers for each inflow station (VINT, VICT, VIST), entitled: DETAILED INDUCED VELOCITY OUTPUT. This output is followed by the total velocity magnitude (VTØT), the blade element angle of attack (ALPHA), the blade element aerodynamic skew angle (SKEW) and blade element inflow angle (PHI) distributions which include the induced velocities. It is titled: DETAILED VELOCITY RELATED OUTPUT.

The above output starting from the Mach cone correction and ending with the inflow angle is repeated for each iteration of the nonlinear circulation matrix solution. The intermediate circulation solution output consists of the nonlinear correction quantities (CØRPHI, CØRVEL, CØRCL) used in the solution technique, the resulting corrected constant vector of the circulation matrix (CØNHSD), the actual correction vector (CFDP), the uncorrected constant vector (CØNST), the current angle of attack (ALPHA), and previous angle of attack (SAVALP), the current lift coefficient (CLSAV), the current circulation (CIRC) and previous circulation (SAVCIR), and the current normalwise induced velocity (VIN) for each inflow station for each propeller position of each propeller for each iteration of the matrix solution. Once the final circulation iteration solution is obtained, the final lift, drag and minimum drag coefficients are printed (CLSAV, CDSAV, CDO). Following this output the total blade forces are listed in terms of the magnitude and direction cosines (FTØT, ALFRAD, ALFPHI, ALFAXL) and the respective lift and drag components of the force (FLTØT, ALFLRD, ALFLPH, ALFLAX, FDTØT, ALFDRD, ALFDPH, ALFDAX). This output is marked: DETAILED BLADE FORCE SUMMARY.

Final Output

The final output consists of tabled values of many of the output items listed in the intermediate printout and integrated performance quantities. This output section is entitled: PROPELLER PERFORMANCE. It is repeated for each performance iteration and presented for each propeller for each propeller position as a function of blade inflow station location (X/R). The description of each of the tabulated items is included on the printout of Appendix B and will not be described here. It is labeled: BLADE SPANWISE VARYING QUANTITIES. Only the descriptions of the sections of integrated quantities will be presented. The first of these integrated sections is labeled BLADE CHARACTERISTICS and contains the blade characteristics for each propeller position for each propeller; thrust per blade ($lb_f$), torque per blade (ft-$lb_f$), power per blade (ft-$lb_f$/sec) and horsepower per blade (hp). Following this section of integrated quantities, the combined (all blades, both propellers) instantaneous values of thrust and power for each propeller position are presented. It is titled: INSTANTANEOUS TOTAL PROPELLER PERFORMANCE FOR PROPELLER POSITION X. This is followed by a section of integrated values averaged over all propeller positions for each propeller, entitled: INTEGRATED PROPELLER CHARACTERISTICS FOR PROPELLER X. This section contains the total thrust ($lb_f$), thrust coefficient ($T/\ n^2D^4$), forward velocity (knots), torque ($ft\text{-}lb_f$), power coefficient ($P/\rho n^3D^5$), advance ratio ($V\pi/\Omega R$), profile torque ($ft\text{-}lb_f$), propeller efficiency (CTXJ/Cp), reference blade angle (degrees), induced torque ($ft\text{-}lb_f$), power ($ft\text{-}lb_f/sec$), horsepower (hp) and the momentum induced velocity (fps). The combined propeller performance follows if coaxial propellers are used. This output is followed by the nacelle and combined nacelle-propeller quantities. These items for the nacelle are the pressure and skin friction drag ($lb_f$), the respective drag coefficients and the combined drag and drag coefficients using the same units and definitions as used for the propellers. The combined nacelle and propeller thrust, thrust coefficient, power and power coefficient and efficiency then follow. Following this output, the force components per blade per unit span are presented in the cylindrical coordinate system ($lb_f/ft$) for each propeller, and labeled: FORCE PER BLADE PER UNIT SPAN.

## Description of Failure Modes

Generally, if the input data is correct and reasonable for the flight condition being investigated, the propeller solution procedure will not fail. To help assist the user in running the computer program, certain failures which could occur because of incorrect data setup or incorrect data values are checked internally by the computer program. If the input is incorrect, diagnostic output will occur to inform the user and allow him to make the required corrections.

### General Input Format

As noted in the section describing the input data setup, certain labelling formats have been specified for the input data. If these formats are violated, explicit output diagnostics will not generally be printed; however, program termination will occur immediately with the last item which was attempted to be read in printed as the last output. Termination on the input of these labels will occur for the following reasons:

(1) Data set labels not in the required order
(2) Data set labels mispunched
(3) Input item labels mispunched
(4) Missing END labels for the data sets

### Missing Input Data

Assuming all of the input data is read in correctly, the program then checks for missing input that is required for successful program execution. The following diagnostic messages could occur if certain data is missing. Explanations of the messages are noted, if required, for clarity.

(1) "PROPELLER DISK DISPLACEMENT NOT INPUT, EXECUTION TERMINATED"

This message informs the user that the hub displacement between the propellers was not input in the coaxial mode of operation.

(2) "RPM NOT INPUT, EXECUTION TERMINATED"

(3) "SOUND NOT INPUT, EXECUTION TERMINATED"

This message informs the user that the freestream value of the speed of sound was not input.

(4) "DENSITY NOT INPUT, EXECUTION TERMINATED"

This message informs the user that the freestream value of the density of air was not input.

(5) "RADIUS NOT INPUT, EXECUTION TERMINATED"

This message informs the user that a blade radius input is missing.

(6) "DPSI NOT INPUT, EXECUTION TERMINATED"

(7) "NUMBER OF WAKE REVOLUTIONS NOT INPUT, EXECUTION TERMINATED"

(8) "NUMBER OF BLADES NOT INPUT, EXECUTION TERMINATED"

Incorrect Data Input

If data is input to the program which is incompatible with the requirements of the computer analysis, diagnostic messages will also occur. The messages are listed below along with explanation, if required.

(1) "POWER COEFFICIENT ITERATION NOT ALLOWED FOR TWO PROPELLERS, EXECUTION TERMINATED"

(2) "THRUST COEFFICIENT ITERATION NOT ALLOWED FOR TWO PROPELLERS, EXECUTION TERMINATED"

(3) "COMPRESSIBLE BOUND VORTEX MODEL NOT FUNCTIONAL FOR TWO PROPELLERS, EXECUTION TERMINATED"

This message informs the user that he has requested a combination of modeling options which are not compatible. The compressible bound vortex model was not derived for coaxial propellers, and thus cannot be used for coaxial propeller configurations.

(4) "INPUT ERROR 360/DPSI IS NOT A MULTIPLE OF B. WILL STOP PROGRAM. JTOT=X, B=X"

This message informs the user that the requested blade azimuth increment is not an integer multiple of 360 degrees. The number of blade azimuth positions (JTOT) and the number of blades (B) that were requested are listed in the locations marked by X respectively.

(5) "***BJTOT IS NOT AN INTEGER MULTIPLE OF THE NUMBER OF PROPELLER DISKS, EXECUTION TERMINATED"

This message informs the user that the number of azimuth intervals between blades is not an integer multiple of the number of propellers. It checks to be sure that for a coaxial configuration, the half blade spacing is an integer multiple of the azimuth increment.

There are also a series of diagnostic messages associated with internal program core allocations. If a combination of input quantities exceeds the internal dimension limits, self-explanatory messages are output which inform the user of the problem, the values input and the allowable limits. Because the messages are self-explanatory, they will not be listed here. The required corrective action will be clear to the user if they do occur.

## Nacelle Portion

This section is intended to describe the general features of the nacelle portion of the PANPER program. The technical aspects of this analysis are described in reference 1. The first subsection describes what problems can be solved and what problems cannot be solved. It also describes any special care which should be used in exercising the various options. The second and third subsections present a detailed description of the input which is required in the operation of the computer program and the interpretation of the printed output. Since any complicated computer program may fail due to inconsistencies in the input or failure of the theory, the computer program is provided with self-diagnostics which notify the user of the type of failure. The last subsection deals with these program diagnostics as well as helpful hints to correct problems which may be encountered.

Since this computer program is intended for a wide variety of users, some note should be made of the nomenclature. The term "duct" refers to any flow passage including inlet nozzles, diffusers, or transition ducts or external flow problems where the outer wall is replaced with the appropriate boundary condition. Typically, such ducts may have struts, compressor or propeller blades, inlet guide vanes, or exit guide vanes and these terms are used almost interchangeably in the discussion. Depending on the user, the duct wall dimensions may be referred to as hub and tip walls or inside diameter (ID) and outside diameter (OD) walls respectively. Some users may use the terms centerbody and outerbody when referring to ID and OD walls respectively. The subscript notation, Fortran symbols, and computer printout generally uses the subscript W for either wall without distinction and H and T for hub and tip wall. Finally, the term "slot injection" refers to the injection of flow tangent to the wall at a discrete axial location, while "mass bleed" refers to injection of flow normal to the wall.

## General Features of the Program

### Types of Fluids

The fluid may be any compressible gas as defined by its thermodynamic properties $\mathcal{R}$, $C_p$, $C_v$, $\mu$, $P_{RL}$, $P_{RT}$. If not otherwise specified, the gas is assumed to be air. The reference conditions for the gas properties must be specified at standard sea-level conditions.

### Types of Flow Situations

External or internal, transonic, turbulent, swirling or nonswirling flows may be calculated, including flows with radial total pressure distortion. Two-dimensional flows may be calculated by constructing an annular duct in which the inner to outer radius approaches 1.0.

### Geometry Options (IØPT3)

The flow through any axisymmetric duct may be calculated provided that the flow is generally in the axial direction. Duct flows normal to the axis of symmetry or which reverse direction cannot be calculated due to logic limitations in Subroutine CØØR. Ducts with sharp discontinuities, such as a step, which produce separation also cannot be calculated.

Provision is made in the program to either read the duct coordinates from input data cards (IØPT3=2), or to calculate the duct coordinates analytically (IØPT3>4) from a few input duct shape parameters. If the duct coordinates are read from input cards, care should be taken that the input coordinates have sufficient smoothness to calculate the first and second derivatives using numerical finite-difference equations. When the second option is used (IØPT3>4), the user must program his own calculation in Subroutine GDUCT. Sample programs (IØPT=1, 3, 4) are given in Subroutine GDUCT for the user's reference. For ducts with no centerbody a zero radius must be specified.

An important restriction to the computer program is that the inlet and exit flow must have no normal pressure gradients produced by streamline curvature, although it may have normal pressure gradients due to swirl. Many ducts do not satisfy this requirement; however, these ducts can still be treated if the duct is extended. For curved annular ducts exhausting to atmosphere, the exit flow may have curvature. This phenomena may be simulated by extending the duct to approximate the curvature of the exit flow.

If the IØPT3=2 option is used, and the number of input points is less than the number of specified streamwise stations, the program smooths the input data and interpolates the required mesh points.

Inlet Flow Options (IØPT1)

The computer program is provided with two methods to describe the inlet flow. When IØPT1=1, the inlet flow is calculated by prescribing the stagnation conditions ($P_o$,$T_o$) on Card No. 6, the inlet Mach number M , the swirl angle $\alpha_1$, and the boundary layer parameters $\delta^*$ and n, which are the boundary layer displacement thickness and power law velocity profile exponent, on Card No. 5, respectively. The core flow is then calculated from isentropic flow relations, and boundary layers added using power law velocity profile relations. When stagnation conditions are not specified, the calculation assumes sea level conditions.

When IØPT1=2, the inlet flow is prescribed from input data cards which specify the stagnation pressure $P_o$, static pressure P, swirl angle $\alpha$, and stagnation temperature $T_o$, as a function of the fractional distance across the inlet. This data need not be specified at equidistant points since a linear interpolation is used to specify the data at the mesh points used in the calculation. If experimental data is not used, care should be taken that the data is self-consistent and that it satisfies the radial equilibrium equation. Since the initial growth of the boundary layer is sensitive to the wall shear stress, data describing the boundary layers should be accurately specified. When this is not possible, boundary layers may be added to each wall by specifying $\delta^*$ and n. Special care should be exercised in using the IØPT1=2 option, with or without the feature of adding in the wall boundary layers. If the stress distribution across the duct is not smooth and realistic, numerical instabilities might originate in the inlet flow and grow rapidly to a point where the calculation is terminated. This may take the form of an unrealistically early separation.

When IØPT1=3, the inlet free stream flow is calculated the same as IØPT1=1. The boundary layers on each wall, however, are calculated from Coles' profiles (reference 3) using Function FCØLES. The IØPT1=4 option is the same as the IØPT1=2 option, except that Coles' profiles are used for the boundary layers.

For IØPT1=1, 2, 3, or 4 there are no restrictions on $\delta^*$ other than it must be greater than zero and that the transverse grid must be chosen such that at least 5 to 10 mesh points exist for $0 \leq Y^+ \leq 10$. A printout of $U^+(Y^+)$ is provided by setting IØPT4=0. In absence of other information a value of $\delta^*$ of one percent of the inlet height is an adequate approximation for a thin initial boundary layer. If the boundary layer thickness is not small compared to half-height, the correct input value of $\delta^*$ must be obtained from other sources such as data correlation, experimental measurements, etc. Most zero pressure gradient boundary layers follow a 1/7th power law profile and it is recommended that this value be used. For IØPT1=3 or 4 in which Coles' profiles are used, a shape factor is computed from the input values is used $\delta^*$ and n. This shape factor is used to compute a wake parameter and a compatible wall stress for use in Coles' profiles. As shown in reference 3, specification of the wake parameter and wall stress uniquely defines the Coles' velocity profile.

### Boundary Conditions ($T_w$, $m_w$)

Either the adiabatic wall or the heat transfer case may be calculated. The program assumes adiabatic walls unless the wall temperature is specified. Any wall temperature distribution may be specified, either on input cards when the duct coordinates are read, or calculated when the duct coordinates are calculated. The case of wall bleed may also be treated in a similar manner; wall bleed flow rate is zero, unless otherwise specified. At the present state of development of the computer code, only the IØPT3=1 option allows a specification of wall temperature as a boundary condition. For all other IØPT3 options adiabatic walls are assumed.

### Force Option

Subroutine FØRCE is provided with two options. For IØPT2 ≠ 0 and NØPPF = 1, the blade force is calculated from data taken from the propeller lifting line portion of the code. For IØPT2 ≠ 0 and NØPPF = 0 the blade forces are read in as input data.

### Failure Modes

In the event of failure in the calculation, the program prints an error message called "diagnostic". These "diagnostics" are in addition to the computer diagnostics and are clearly labeled as such. These "diagnostics" terminate the calculation only when very serious. A list of these "diagnostics" appears in a later section. Included with this list is an identifying number for the "diagnostic", the location (Subroutine), and the immediate cause of the failure. Where possible, suggestions are made to correct the calculation.

### Debug Options (IDBGN)

Auxiliary printout which was originally used to debug the computer program is available to the user by setting the appropriate IDBGN option. However, the user must refer to the program listing or compilation to determine the meaning of this printout.

## Grid Selection

The grid selection parameters appear on the third input card and are given by DDS, KL, JL, KDS. The number of streamwise stations is divided into a coarse grid of JL $\leq$ 100. The number of streamlines including the wall boundaries is given by KL $\leq$ 100 points and a fine grid of JL*KDS points. The solution is numerically stable; however, truncation errors may get large if too large a streamwise step size is used. The streamwise step size may be made smaller without recalculating the coordinate system by increasing KDS. It should be noted that computing time is proportional to JL*KDS. The parameter DDS distorts the normal coordinate by placing more streamlines near the wall.

## Mesh Distortion

The numerical solution of turbulent boundary layers requires accurate integration of the mean profile in the turbulent mixing layer. For high Reynolds number flows, practical considerations require distributing more mesh points near the wall in some systematic manner. This is done using an exponential transformation given by

$$n(\eta) = \frac{(c+1/2)\exp\left[2\ \ln\left(\frac{c+1/2}{c-1/2}\right)(\eta-1/2)\right] - (c-1/2)}{1+\exp\left[2\ln\left(\frac{c+1/2}{c-1/2}\right)(\eta-1/2)\right]} \qquad (1)$$

where

$$0 \leq n \leq 1$$

$$0 \leq \eta \leq 1$$

The parameter c is chosen so as to place the first mesh point at approximately $Y^+ = 1$. Then for equal increments in $\Delta\eta$, equation (1) distributes the mesh points $\Delta n$ so as to place more mesh points near the wall.

## Separation

The separation point is determined when the streamwise component of wall stress goes to zero. However, the calculation can continue past the separation point. When the region of reverse flow becomes too large, greater than 2.0 percent, the calculation stops.

## Description of Input

This subsection describes the loading of input data cards for running the nacelle portion of the computer program. The input specification follows the convention that a blank or zero value for any parameter implies no action by the computer program. Numbered cards must be loaded. The remaining cards must be loaded only if the proper option is selected. Care should be taken in loading the program because of the input changes depending on the options chosen in the second data card. Multiple cases can be run simply by stacking the cases in order. The last case is followed by two blank cards.

### Card No. 1: Title Card

| Name | Col. | Format | Comments: |
|---|---|---|---|
| TITLE | 1-72 | 12A6* | Any alphanumeric characters. |

### Card No. 2: Option Card

| Name | Col. | Format | Comments: |
|---|---|---|---|
| IØPT1 | 1-2 | I2 | (FLØWIN Option)<br>IØPT1=3 The inlet flow is computed by specifying the data on card 5.<br>IØPT1=4 The inlet flow is read from 2xKLL data cards following card 5.<br>IØPT1=9 Laminar flow, inlet flow is calculated using a Blasius profile. |
| IØPT2 | 3-4 | I2 | (FØRCE Option)<br>IØPT2=0 No blades or struts exist in the duct and these cards are not loaded.<br>IØPT2=3 The strut forces are input on cards (2xKLL cards following card 3).<br>IØPT2=4 The blade forces are calculated from lifting line theory if NØPPF=1. If NØPPF=0 blade forces are read from data cards. |
| IØPT3 | 5-6 | I2 | (GDUCT option)<br>IØPT3=1 Calculate a straight annular duct<br>IØPT3=2 Read coordinates<br>IØPT3=3 Calculate a straight wall annular diffuser<br>IØPT3=4 Do not use<br>IØPT3=5 Calculate curved wall diffuser No. 1.<br>IØPT3=8 Straight walled duct |

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* 12A6 UNIVAC system
18A4 IBM systems

Card No. 2: Option Card (Cont'd)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| IØPT4 | 7-8 | I2 | Print solution every IØPT4 stations. For example, if IØPT4=3 every third station is printed. If IØPT4=1 every station is printed. If IØPT4=-1 additional output at each station is printed. |
| IØPT5 | 9-10 | I2 | Strut data input (see IØPT2=3) used to calculate strut forces from experimental data measured upstream and downstream of strut.<br>IØPT5=1 Read in required profiles.<br>IØPT5=2 The upstream and downstream strut data cards are identical to the inlet and exit flow cards and need not be loaded. |
| IØPT6 | 11-12 | I2 | IØPT6=0 Strut force plus thickness effects.<br>IØPT6=1 Strut thickness effects only. |
| IØPT7 | 13-14 | I2 | Axisymmetric compressible streamline curvature corrections.<br>0 = No curvature correction<br>1 = Curvature correction |
| IØPT8 | 15-16 | I2 | WBLEED option.<br>= 0 No Bleed<br>= 1 Bleed OD wall<br>= 2 Bleed ID wall<br>= 3 Bleed OD and ID wall |
| IØPT9 | 17-18 | I2 | IØPT9=0 Approximate CØØR calculation.<br>IØPT9=1 Exact CØØR calculation.<br>IØPT9=2 Store CØØR calculation on mass storage device (Unit 9) and stop.<br>IØPT9=3 Read CØØR calculation from mass storage device (Unit 9) and stop.<br>For normal running, set IØPT9=1. Subroutine CØØR is described in a later section. |
| IØPT10 | 19-20 | I2 | IØPT10=1 Internal flow problem.<br>IØPT10=0 External flow problem. |
| IØPT11 | 21-22 | I2 | IØPT11=1 External flow problem.<br>IØPT11=0 Internal flow problem. |

| Name | Col. | Format | Comments: |
|---|---|---|---|
| IØPT12 | 23-24 | I2 | Not used. |
| IØPT13 | 25-26 | I2 | Not used. |
| IØPT14 | 27-28 | I2 | Not used. |
| IØPT15 | 29-30 | I2 | Start flow calculation at station IØPT15. Default = 1.0. |
| IØPT16 | 31-32 | I2 | End flow calculation at station IØPT16. Default = JL. |
| IØPT17 | 33-34 | I2 | Not used. |

Card No. 3: Mesh Parameters

| | | | |
|---|---|---|---|
| DDS | 1-10 | F10.3 | Mesh distortion parameter, default determined internally. |
| KL | 11-13 | I3 | Number of streamlines including wall, $2 \leq KL \leq 100$. |
| JL | 14-16 | I3 | Number of streamwise stations, $JL \leq 100$. |
| KDS | 17-19 | I3 | Number of steps per streamwise station. Default = 2. |
| KLL | 20-22 | I3 | Number of streamlines of data input (see IØPT1, IØPT2). If KLL < KL, inlet flow is interpolated from KLL inlet data cards on the KL streamlines used for calculating flow. $KLL \leq 31$. |
| JLAST | 23-25 | I3 | Number of CØØR records stored on drum. Used for tape storage of coordinate functions. Not used in this version. |
| JLPTS | 26-28 | I3 | Number of input duct coordinate points, if IØPT3 = 2. Note: If JLPTS < JL, points are smoothed and interpolated. Not used in this version. |
| LFILE | 29-31 | I3 | Case stored on tape file LFILE used for tape storage of coordinate functions. Not used in this version. |

Card No. 4: GDUCT

| Name | Col. | Format | Comments: |
|---|---|---|---|
| | | | These input cards are read in subroutine GDUCT as programmed by the user. |

The following duct geometries (designated as IØPT3=1,2,3, and 5) have been programmed (see figure 6).

Card No. 4: (IOPT3=1) Straight Annular Duct

| Name | Col. | Format | Comments: |
|---|---|---|---|
| Z1 | 1-10 | F10.0 | Length (ft) |
| RH1 | 11-20 | F10.0 | Centerbody radius (ft) |
| RT1 | 21-30 | F10.0 | Outerbody radius (ft) |
| TWH | 31-40 | F10.0 | Centerbody wall temperature (deg R) |
| TWT | 41-50 | F10.0 | Outerbody wall temperature (deg R) |
| AMWH | 51-60 | F10.0 | Centerbody wall bleed ($lb/ft^2$ sec) |
| AMWT | 61-70 | F10.0 | Outerbody wall bleed ($lb/ft^2$ sec) |

Card No. 4: (IØPT3=2) Arbitrary Duct Input

| Name | Col. | Format | Comments: |
|---|---|---|---|
| Z1 | 1-10 | F10.0 | Duct length (ft) |
| RNOPE | 11-20 | F10.0 | One more than the number of curve fits used for smoothing the input geometry. Default 5.0. |
| XNOSE | 21-30 | F10.1 | Distance to nacelle nose (ft) |

Cards Following Card No. 4: (IØPT3=2) For JLPTS equally spaced points, thus Z(J)=Z1*(J-1)/(JLPTS-1)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| R(1,1,J) | 1-80 | 8F10.0 | Outerbody radius (ft) |
| R(2,1,J) | 1-80 | 8F10.0 | Centerbody radius (ft) |

Card No. 4: (IØPT3=3) Straight Wall Annular Diffuser

| Name | Col. | Format | Comments: |
|---|---|---|---|
| Z1 | 1-10 | F10.0 | Duct length (ft) |
| RH1 | 11-20 | F10.0 | Centerbody radius (ft) |
| RT1 | 21-30 | F10.0 | Outerbody radius (ft) |
| ZTHRO | 31-40 | F10.0 | Length of throat (ft) |
| ANGH | 41-50 | F10.0 | Centerbody wall angle (deg) |
| ANGT | 51-60 | F10.0 | Outerbody wall angle (deg) |

Card No. 4: (IØPT3=5) Curved Wall Annular Diffuser No. 1

| Name | Col. | Format | Comments: |
|---|---|---|---|
| Z1 | 1-10 | F10.0 | Duct length (ft) |
| RT1 | 11-20 | F10.0 | Inlet outerbody radius (ft) |
| RH1 | 21-30 | F10.0 | Inlet centerbody radius (ft) |
| RTL | 41-50 | F10.0 | Exit centerbody radius (ft) |
| RHL | 51-60 | F10.0 | Exit outerbody radius (ft) |
| AT | 61-70 | F10.0 | Power outerbody wall AT_2 |
| AH | 71-80 | F10.0 | Power centerbody wall AH_2 |

Card No. 4: (IØPT3=6) Not Used

Card No. 5: Inlet Flow Distribution (See figure 7)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| AMS1 | 1-10 | F10.0 | Nominal inlet Mach number |
| ALP1 | 11-20 | F10.0 | Nominal swirl angle at hub (deg to axis) |
| DSH | 21-30 | F10.0 | Boundary layer displacement thickness on hub wall (ft) |

| Name | Col. | Format | Comments: |
|---|---|---|---|
| DST | 31-40 | F10.0 | Boundary layer displacement thickness on tip wall (ft) |
| ANH | 41-50 | F10.0 | Power law exponent for hub boundary layer |
| ANT | 51-60 | F10.0 | Power law exponent for tip boundary layer. For boundary layers of approximately 10 percent of inlet height, nominal values for DSH and DST are 0.0125 times inlet height and ANH, ANT equal to 7.0. |

<u>2xKLL Inlet Flow Cards Following Card 5</u> (Only if IØPT1=4)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| BINPUT(1,K) | 1-10 | F10.0 | Fractional distance across duct Y |
| BINPUT(2,K) | 11-j20 | F10.0 | Total pressure (lb/ft$^2$ abs) $P_o$ |
| BINPUT(3,K) | 21-30 | F10.0 | Static pressure (lb/ft$^2$ abs) P |
| BINPUT(4,K) | 31-40 | F10.0 | Swirl angle to axis (deg) $\alpha$ |
| BINPUT(5,K) | 41-50 | F10.0 | Total temperature (deg R) $T_o$ |

The first KLL cards describe the inlet flow. The second KLL cards describe the exit flow. If the exit flow is not known, KLL blank data cards must be used. If $\delta_H^*>0$ on Card 5, boundary layers are added according to Card 5.

<u>Blade Row Data Card Following Card 5</u> (Only if IØPT≠0)

This sequence of data cards is repeated for each blade row. This data must be consistent with the propeller input geometry.

| Name | Col. | Format | Comments: |
|---|---|---|---|
| ZCLI | 1-10 | F10.0 | Axial location of blade centerline |
| NBLADE | 11-13 | I3 | Number of blades |
| ISHAPE | 14-16 | I3 | Blade shape index |

| Name | Col. | Format | Comments: |
|---|---|---|---|
| NUM | 17-19 | I3 | Number of points defining blade segment boundaries |
| OMEGZ1 | 20-29 | F10.0 | Rotational velocity (rpm) |
| LROW | 30-32 | I3 | Blade row counter |
| NROW | 33-35 | I3 | Number of blade rows |

Blade Row Geometry Cards

The blade row geometry cards are read in if the nacelle portion of the program is operating without the propeller portion.

NUM times the blade row geometry cards (root to tip) noted below, follow each blade row data card (IØPT2≠0, NØPPF=0)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| CONST1(1,K) | 1-10 | F10.0 | Blade radius (ft) |
| CONST1(2,K) | 11-20 | F10.0 | Chord angle to blade face (deg) |
| CONST1(3,K) | 21-30 | F10.0 | Chord (ft) |
| CONST1(4,K) | 31-40 | F10.0 | Thickness/Chord |
| CONST1(6,K) | 41-50 | F10.0 | Axial location at blade quarter chord (ft) |

Arbitrary Strut Thickness Distribution (ISHAPE = 4)

| Name | Col. | Format | Comments |
|---|---|---|---|
| KBLADE | 1-10 | I10 | No chordwise stations (KBLADE $\leq$ 50) |

Chordwise location

| Name | Col. | Format | Comments: |
|---|---|---|---|
| X(K) | 1-80 | 8F10.0 | Chordwise location |
| Y(K) | 1-80 | 8F10.0 | Thickness/maximum thickness distribution |

2xKLL Strut Data Cards Following (IØPT5 ≠ 0, IØPT2 = 3)

| Name | Col. | Format | Comments: |
|---|---|---|---|
| AINPUT(1,K) | 1-10 | F10.0 | Fractional distance across duct Y |
| AINPUT(2,K) | 11-20 | F10.0 | Stagnation pressure (lb/ft$^2$ abs) $P_o$ |
| AINPUT(3,K) | 21-30 | F10.0 | Static pressure (lb/ft$^2$ abs) P |
| AINPUT(4,K) | 31-40 | F10.0 | Swirl angle to axis (deg) $\alpha$ |
| AINPUT(5,K) | 41-50 | F10.0 | Stagnation temperature (deg R) $T_o$ |
| | | | The first KLL cards describe the inlet flow of the strut row. The second KLL cards describe the exit flow (see Card 2). |

Card No. 6: Performance Point

If this card is left blank, the default values shown in parentheses are used.

| Name | Col. | Format | Comments: |
|---|---|---|---|
| PRESO | 1-10 | F10.0 | Inlet stagnation pressure (2117. lb/ft$^2$ abs) |
| TEMPO | 11-20 | F10.0 | Inlet stagnation temperature (519. deg R) |
| ACI | 21-26 | F6.0 | Clauser constant (0.016) |
| AKI | 27-32 | F6.0 | Von Karman constant (0.41) |
| API | 33-38 | F6.0 | Van Driest constant (26.0) |
| PRTI | 39-44 | F6.0 | Turbulent Prandtl number (0.8) |
| PRLI | 45-50 | F6.0 | Laminar Prandtl number (0.9) |
| CPR | 51-60 | F10.0 | Specific heat at constant pressure (5997 ft$^2$/sec$^2$) |
| CVR | 61-70 | F10.0 | Specific heat at constant volume (4283 ft$^2$/sec$^2$) |

| Name | Col. | Format | Comments: |
|---|---|---|---|
| VISCR | 71-80 | F10.0 | Viscosity (0.37E-06 lb/sec $ft^2$) at Standard Conditions. |

Card No. 7: Wall Bleed Card

| | | | |
|---|---|---|---|
| CDISH | 1-10 | F10.0 | Discharge coefficient for holes (dimensionless) CDISH < 1.0 |
| AHAS | 11-20 | F10.0 | Ratio of hole area to surface area |
| TTP | 21-30 | F10.0 | Plenum total temperature (°F) |
| PTP | 31-40 | F10.0 | Plenum total pressure (psta) |
| XBF | 41-50 | F10.0 | Wall distance - start wall bleed (ft) |
| XBL | 51-60 | F10.0 | Wall distance - end wall bleed (ft) |

Blade Force Card

NUM blade force cards following Card 6 (only if IØPT2≠0 and NØPPF≠0). Repeat for each blade row.

| Name | Col. | Format | Comments: |
|---|---|---|---|
| FRCI(N,1) | 1-10 | F10.0 | Radial force/span |
| FRCI(N,2) | 11-20 | F10.0 | Tangential force/span |
| FRCI(N,3) | 21-30 | F10.0 | Axial force/span |

N=1, NUM

Description of Output

## Title Page

The output presented on this page is self-explanatory except for the following variables

$$m_1 = \int_{r_H}^{r_T} g_B \rho\, U_s dr$$

$$a_1 = \int_{r_H}^{r_T} g_B dr$$

$$\bar{p}_1 = \frac{1}{m_1} \int_{r_H}^{r_T} g_B \rho\, U_s p_1 dr = \text{PRES1}$$

$$\bar{q}_1 = \frac{1}{m_1} \int_{r_H}^{r_T} g_B \rho\, U_s (1/2\ \rho\, U_1^2) dr = \text{DYNP1}$$

$$\bar{M}_1 = \frac{1}{m_1} \int_{r_H}^{r_T} g_B \rho\, U_s M_1 dr = \text{MACH1}$$

$$\text{WFL}\phi = 32.2\ N_B m_1$$

$$\text{USR} = m_1/\rho_r/a_1 = U_r$$

$$REY = r_r \; U_r/\rho_r/\mu_r$$

Wall Conditions Page

This page presents a table of Z, $r_T$, $\mathring{m}_T$, $T_T$, $r_H$, $\mathring{m}_H$, $T_H$ which was calculated in Subroutine GDUCT.

Blade Geometry Page (If IØPT2 ≠ 0)

This page presents a table of blade geometry properties at each discrete point of the lifting line. These properties are radius $r_{CL}$, stagger angle $\alpha_{SL}$, chord $C_L$ thickness T/C, and axial location $Z_{CL}$. Also, the number of blades per row and the blade shape are printed.

Gap Average Inviscid Flow Page

This page presents the solution for the inviscid flow variables across the duct at selected stations depending on IØPT4. A table of values for Y, $P_o$, P, $\alpha$, $T_o$, T, M, U, $U_s$, $U_z$, $U_r$, speed of sound a, and P are given. Also printed is the pressure coefficient at the inner wall where

$$C_{PW} = \frac{2}{\gamma M_\infty^2} \left[ \left( \frac{2+(\gamma-1)M_\infty^2}{2+(\gamma-1)M^2} \right)^{\frac{\gamma}{\gamma-1}} -1 \right]$$

where $M_\infty$ = freestream Mach number.

Inviscid Nacelle Drag Page

This page prints the nacelle pressure drag calculation of the nacelle.

Nacelle Wake Corrections Page (If IØPT2 ≠ 0)

This section indicates the location of the propeller lifting line in the (s, n, $\phi$) coordinate system. The flow conditions of the lifting line are also presented. These problems are $U_{r_L}$, $U_{z_L}$, $\rho_L$, $a_{z_L}$, sin(T), and cos(T) where $T = \theta$.

## Gap Average Viscous Flow Page

This page presents the solution for the flow variables across the duct at selected streamwise stations depending on IØPT4. A table of values for Y, $U_S$, $U_\phi$, $\alpha$, $\Pi$, $\theta$, M, $\Pi_0$, $\Theta_0$, $C_p$ are given where

$$C_p = (\Pi - \Pi(0,0))/\bar{q}_1$$

In addition, the wall values for Z, $\dot{m}$, $C_{f\phi}$, $C_{fs}$, Q are printed, where $C_{f\phi}$ and $C_{fs}$ are defined by

$$C_{f\phi} = \tau_{n\phi}/\bar{q}_1$$

$$C_{fs} = \tau_{ns}/\bar{q}_1$$

The one-dimensional characteristics of the flow are also given: area ratio $A/A_1$, Mach number (isentropic flow) $M_1$, incompressible and compressible flow pressure coefficient CPINC and CPCØMP.

## Wall Surface Conditions Page

This output page presents a summary of the wall conditions along the length of the duct. This includes $Z_H$, $C_{PH}$, $C_{FH}$, $T_{WH}$, $A_{SH}$, $Q_{SH}$, $Z_T$, $C_{PT}$, $C_{FT}$, $T_{WT}$, $A_{ST}$, $Q_{ST}$.

## Wall Radiation Summary Page

This output page presents a summary of information which is useful in computing radiation effects. The wall temperature $T_{WH}$, $T_{WT}$, on a differential area $dA_H$, $dA_T$, located at point $(Z_H, r_H)$, $(Z_T, r_T)$ with the sin (wall angle) is given.

## Viscous Nacelle Drag Page

This page prints the nacelle pressure drag, pressure drag coefficient, friction drag, and friction drag coefficient of the nacelle.

IDBGØ Pages

Intermediate printouts which were used to debug the program may be called by setting the debug options IDBGØ=1. IDBGØ may be specified on the option input card. The user should refer to the program listing in each subroutine to determine the printout variables.

| Debug Print Out | Subroutine - Purpose |
|---|---|
| IDBG1 | TURB - Debug |
| IDBG2 | FCØRCT - Debug |
| IDBG3 | FLØWIN - Debug |
| IDBG4 | Not Used |
| IDBG5 | SØLVI - Debug |
| IDBG6 | CØØR - Debug |
| IDBG7 | FØRCE - Debug |
| IDBG8 | MINVRT - Debug |
| IDBG9 | SMØØTH - Debug |
| IDBG10 | GDUCT - Debug |
| IDBG11 | Not Used |
| IDBG12 | SØLVI - Debug #2 |
| IDBG13 | CKINPT - Debug |
| IDBG14 | Set Number of Streamlines |
| IDBG15 | Automatic Step Size Debug, Number of Streamlines Calculated (default = 25) |
| IDBG16 | Suppress Freestream Instability |
| IDBG17 | Not Used |
| IDBG18 | GEØMCL - Debug |
| IDBG19 | WAKCØR - Debug |
| IDBG20 | PERFNA and PERFN2 - Debug |

## Description of Failure Modes

The nacelle portion of the computer program can diagnose the cause of certain failure modes for this portion of the analysis and a printed message of the following form is given.

**DIAGNOSTIC NO. XX FOR ANNULAR DIFFUSER DECK**

The number XX identifies the type of failure from the list below.

1) IØPT3 OUTSIDE RANGE OF ALLOWABLE DUCT OPTIONS

   This failure occurs in Subroutine ALTMN. The input option must be between $1 \leq$ IØPT3 $\leq 6$.

2) No solution exists in AMFOR

   This failure occurs in Subroutine AMFOR. This subroutine solves the Mach number function

$$N = M\left(1 + \frac{\gamma-1}{2}\right)^{1/2} / \left(1 + \gamma M^2\right)$$

   for M given N. This function has a maximum at $M = 1$. Hence

$$N(1) = [2(1 + \gamma)]^{-1/2}$$

   Solutions do not exist for values of $N > N(1)$.

3) MASS FLOW EXCEEDS THE MAXIMUM MASS FLOW POSSIBLE

   This failure occurs in Subroutine AMINLT which solves the Mach number function

$$N = M\left(1 + \frac{\gamma-1}{2} M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

   for M given N. This function has a maximum for $M = 1$ given by

$$N(1) = \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

   corresponding to choked flow.

4) Not Used

5) FOR BEST RESULTS ADD A STRAIGHT ANNULAR CHANNEL INLET

This diagnostic occurs in Subroutine CØØR1. In the construction of the duct coordinates, it is assumed that the inlet has no curvature as shown in figure 8. This is not a fatal error because small inlet curvatures may be tolerated. In order to avoid problems, the best procedure is to add a straight annular section to the inlet as shown by the dotted line in figure 8.

6) PROGRAM ASSUMES INLET FLOW HAS CURVATURE

This diagnostic occurs in Subroutine CØØR1. Same as diagnostic 5.

7) WALL CURVATURE IS TOO LARGE AT STATION X.

This diagnostic occurs in Subroutine CØØR1 usually with bad input data describing the duct contour resulting in a numerically discontinuous change in wall curvature shown in figure 2.

8) Not Used

9) GREATER THAN 1. PERCENT NORMAL PRESSURE GRADIENT ERROR RECALCULATE STATIC PRESSURE

This diagnostic occurs in Subroutine ERPIN. This subroutine integrates the radial equilibrium equation

$$P_T - P_H = \gamma M_r^2 \int_o^1 \left[ \frac{-\rho}{V} \frac{\partial V}{\partial n} U_s^2 + \frac{\rho}{R} \frac{\partial R}{\partial n} U_\phi^2 \right] \frac{d\eta}{XY}$$

and compares $(P_T - P_H)$ to that computed for the input inlet flow $(P_T - P_H)_1$. If the error given by

$$E = \left| 1 - \frac{P_T - P_H}{(P_T - P_H)_1} \right|$$

is greater than 0.01, the input initial static pressure distribution is replaced by the above pressure equation and the flow is recalculated.

10) Not Used

11) MASS FLOW REQUIRED EXCEEDS MAXIMUM MASS FLOW POSSIBLE

This diagnostic occurs in Subroutine CKINPT. Choked flow may exist in the duct, and this diagnostic will be printed out. The weight flow must be reduced.

12) PRESSURE RISE EXCEEDS PERMISSIBLE PRESSURE RISE

This diagnostic occurs in Subroutine CKINPT. This error occurs with the failure by the deck to properly set up flow entering duct. Check input for errors.

13) Not Used

14) BOUNDARY LAYER TOO THIN FOR MESH SPACING

This diagnostic occurs in Subroutine FLØWIN. The viscous flow calculation requires a finite initial boundary layer thickness. In addition, it requires enough mesh points to describe the inlet boundary velocity profile. The deck assumes arbitrarily that at least five mesh points are required. Thus, if this diagnostic occurs, increase the number of mesh points, KL, increase the mesh distortion parameter, DDS, or increase the assumed inlet boundary layer thickness. Setting DDS = 0 automatically sets the mesh distortion parameter for turbulent flow.

15) TOTAL PRESSURE IS LESS THAN STATIC PRESSURE

This diagnostic occurs in Subroutine FLØWIN. A check is made on the input data for IØPT1 = 4, to be sure that $P_T > P$.

16) INPUT DATA NOT IN RADIAL EQUILIBRIUM CORRECTIONS APPLIED TO STATIC PRESSURE

This diagnostic occurs in Subroutine FLØWIN. A check is made of the input data for IØPT1 = 4. If the data is not in radial equilibrium, it is assumed that the static pressure is in error, and the other inlet data is correct. Then the static pressure is computed from

$$\frac{d\Pi}{d\eta} = 2\,\frac{\gamma}{\gamma-1}\left[\frac{-1}{XV}\,\frac{\partial V}{\partial n}\cos^2\alpha - \frac{1}{XR}\,\frac{\partial R}{\partial n}\sin^2\alpha\right]\Pi\left(\left(\frac{\Pi_o}{\Pi}\right)^{\frac{\gamma-1}{\gamma}}-1\right)^{1/2}$$

with the ID wall static pressure as a boundary condition.

17) INPUT DDS MUST BE SPECIFIED

This diagnostic occurs in Subroutine FNØRM. At this time there is no algorithm to automatically select the mesh distortion parameter DDS for laminar flow.

18) BLADE DATA ERROR IN CKINPT ROUTINE

This diagnostic occurs in Subroutine CKINPT. Blade data input is incorrect. It must be rearranged with increasing Y.

19) NO UNIQUE SOLUTION FROM MINVRT

This diagnostic occurs in Subroutine MINVRT. If the matrix set up to solve the turbulent flow solution is singular, no solution can be obtained. This may occur from numerical truncation error problems.

20) LEADING OR TRAILING EDGE INDEX OF STRUT OUT OF RANGE

This diagnostic occurs in Subroutine SLETE. In order to compute blade forces, the strut must be wholly contained within the duct length. This problem may be eliminated by extending the duct length in a realistic manner as shown in figure 10.

21) Not Used

22) Not Used

23) BOUNDARY LAYER OVERLAP OR TOO LARGE

This diagnostic occurs in Subroutine FLØWIN. For internal flow, the sum of the two boundary layer thicknesses must be less than the duct inlet height. Check input data.

24) SET TOTAL TEMPERATURE, PRESSURE; ANGLE TO VALUE AT EDGE OF BOUNDARY LAYER - CORRECTIONS APPLIED

This diagnostic occurs in Subroutine FLØWIN. For IØPT1 = 4, calculated boundary layer profiles are matched to experimentally measured inlet flow. Good matching occurs only if the inlet flow data shows constant $P_T$ in the boundary layer region as shown in figure 11 by the dotted line.

25) TRUNCATION ERROR CANNOT BE REDUCED BY STEP SIZE

This diagnostic occurs in Subroutine SØLVI. When the step size KDS is not specified, it is automatically selected by checking the truncation error at each step. When an instability occurs, the program attempts to reduce the truncation error by reducing the streamwise step. If the truncation error cannot be reduced below a minimum value, the calculation stops with this error message.

26) NUMERICAL INSTABILITY

This failure occurs in Subroutine FCØRCT. Temperature and pressure are checked for negative values. Calculation stops with this error.

27) Not Used

28) Not Used

29) SOLUTION REQUIRES REVERSE FLOW, INCREASE WFLOW

This diagnostic occurs in Subroutine CKINPT. For flows with radial pressure gradients, there is a minimum weight flow below which reverse flow exists. This is corrected by increasing weight flow.

30) Not Used

31) Not Used

32) NORMAL COORDINATE OF LIFTING LINE IS NEGATIVE
BLADE DATA DOES NOT CORRESPOND TO GEOMETRY OF DUCT

This diagnostic occurs in Subroutine GEØMCL. Blade geometry was inputted incorrectly to program. This will produce a fatal error.

# DETAILED PROGRAM DOCUMENTATION

This section is intended to provide sufficient documentation to the user so that the internal operation of the program can be related to the analysis presented in the technical report (Reference 1). It is assumed that the user desiring this information has the required background in aerodynamics and computational fluid dynamics or access to the required technical support to understand the pertinent aspects of the program code as they relate to the theory.

This section contains two major subsections, the propeller solution portion and the nacelle solution portion, respectively. These subsections contain, (1) an alphabetic list of the subroutines and external functions and a brief desctiption of each, (2) a more detailed description of each subroutine in alphabetical order and, (3) a description of the label common blocks and variables used in alphabetical order. Flow charts and figures are provided in the subroutine descriptions where deemed necessary to understand the program structure and technical features.

The subroutines and external functions are all described with the same format using the name of the subroutine with its argument list given as a title. A list of options and FORTRAN symbols used only in the named subroutine are then given. Any special or additional theory used in the subroutine is presented but well known numerical methods are not described.

## Propeller Program

Within this section brief descriptions of the subroutines used in the lifting line portion of the analysis are presented followed by the labeled common blocks used in the analysis. The objective of a particular subroutine is noted, along with a list of symbols which are not in labeled common blocks and which are felt to be necessary for the understanding of the particular subroutines in question. These lists of symbols have been kept brief. A brief explanation of the theory is also included for selected subroutines. Generally, descriptions of the options which control the flow of a particular subroutine are also included. The subroutines are presented in alphabetical order. The labeled common blocks used in the analysis are also listed in alphabetical order with brief descriptions of each variable referenced. Brief flow diagrams of the major computational subroutines (GCWAKE, PRØP, SØLVEL and SØLVEN) are included in the description of each of these subroutines.

### List of Subroutines

| Name | Description |
|---|---|
| AFFIDC | Calculate blade activity factor and integrated design lift coefficient |
| AF65A | Calculate cascade airfoil data |
| AIRFL | Control type of airfoil data to be used |
| AIRFLT | Airfoil package control routine |
| AIRFMN | Main airfoil package control routine for interfacing interpolation, cascade data and isolated airfoil data |
| AIR23 | Control lift and drag calculations for airfoil type number 23 |
| AIR24 | Control lift and drag calculations for airfoil type number 24 |
| ASSOC | Test input variable label |
| AVECTR | Create a column vector from scalar input values |
| BILINE | Interpolation routine |
| BLDGEØ | Calculate blade geometry |

| Name | Description |
| --- | --- |
| CALCGC | Calculate geometric influence coefficient |
| CALWAK | Control flow of wake geometry calculations |
| CASARF | Control routine for analytical cascade correction |
| CASDAT | Control selection of type of cascade data |
| CHKINP | Check input parameters for obvious errors |
| CLFACT | Calculate lift curve slope factor |
| CØMBWK | Calculate effective displacement of bound vortex |
| CPITER | Calculate blade angle for next power performance iteration |
| CRØSSP | Calculate cross product of two vectors |
| CSCD1 | Cascade airfoil data subroutine (reference ___) |
| CTITER | Calculate blade angle for next thrust performance iteration |
| DØTP | Calculate dot product of two vectors |
| DRAG24 | Calculate drag coefficient for airfoil type number 24 |
| DZRØAL | Calculate lift offset due to cascade influence |
| ELIP2 | Approximate Elliptic Integral of second kind |
| FINAIR | Control final airfoil data calculation |
| FSQRT | Calculate magnitude of three component vector |
| FVECTR | Calculate blade forces |
| GAUSS | Solve system of simultaneous linear equations (direct method) |
| GCBØUN | Calculate geometric influence coefficients for bound vortex |

| Name | Description |
| --- | --- |
| GCCØRE | Calculate vortex core model |
| GCFILA | Calculate geometric influence coefficient for trailing vortex filament |
| GCWAKE | Control basic flow of geometric influence coefficient calculations |
| G400LD | Calculate lift and drag using linearized airfoil data |
| INDVEL | Calculate induced velocities |
| INTIAL | Initialize data and print out selected quantities |
| ISØAFL | Control selection of isolated airfoil data type |
| ISØARF | Control isolated airfoil data calculation |
| LDDATA | Read in propeller data |
| LIFT24 | Calculate lift coefficient for airfoil type number 24 |
| LINEAR | Linear interpolation algorithm |
| LINTER | Control interpolation of data arrays |
| MVMULT | Multiply single dimension vector with two dimensional vector |
| MCØNE | Calculate Evvard Tip Relief Correction |
| NSTACØ | Calculate Mach cone intersection station index |
| PAGE | Advance output device to new page |
| PCHØUT | Punch spanwise distributions of aerodynamic quantities |
| PERFØR | Calculate propeller performance |
| PERIØD | Calculate propeller periodicity quantities |

| Name | Description |
|---|---|
| PERPRT | Print spanwise distributions of aerodynamic and geometric quantities |
| PHICAL | Calculate wake azimuth information |
| PLABEL | Print a label |
| PN | Calculate a special function |
| PRØP | Main propeller subroutine |
| PRDATA | Print label and vector |
| PRG400 | Write output quantities for aeroelastic response analysis (reference 12) |
| PRINTP | Print label and vector |
| PRTF15 | Print label and floating point variable vector, maximum of 15 |
| PRTF16 | Print label and floating point variable vector, maximum of 16 |
| PRTGCM | Print geometric influence coefficient matrix |
| PRTI15 | Print label and integer index for maximum of 15 integers |
| PRTI16 | Print label and integer index for maximum of 16 integers |
| PRTLF | Print label field and single floating point variable |
| PRTLI | Print single integer and label |
| PRTRZW | Print radial or axial wake coordinates |
| PRWZW | Print wake geometry |
| RDSCAL | Controls read of scalar inputs |
| RDVECT | Controls read of vector inputs |

| Name | Description |
|---|---|
| READWR | Reads a vector string and outputs it to printer |
| RELAXG | Relaxation subroutine for circulation solution |
| REDMAT | Read geometric influence coefficient in matrix form from disc |
| RWZWIN | Input wake geometry from cards |
| RWZW1 | Calculate classical or modified classical wake |
| RWZW7 | Calculate generalized wake |
| SBFUNC | Special function subroutine for cascade data, reference 11 |
| SETMAT | Set up geometric influence coefficient matrix |
| SIEDEL | Solve system of simultaneous equations (indirect method) |
| SØLVEL | Control linearized aerodynamic solution |
| SØLVEN | Control nonlinear aerodynamic solution |
| SØLVIT | Control solution procedure |
| SPLIN3 | Interpolate with spline fit |
| STARC | Convert design lift coefficient to equivalent camber angle |
| STØRE | Transfer data from one vector to another |
| SWPCØR | Calculate conical flow theory tip loss |
| THITER | Control blade pitch iteration |
| TITER | Extrapolate or interpolate on blade pitch angle versus $C_T$ or $C_p$ |
| TITLE | Print title information |
| UNBAR | Interpolation routine |

| Name | Description |
|---|---|
| UNINT | Interpolation routine |
| VECTØR | Compute velocity and velocity related quantities including induced velocities |
| VVECTR | Compute velocity and velocity related quantities including induced velocities |
| WAKMØD | Modify wake geometry due to nacelle influence |
| WRITGC | Write geometric influence coefficient to disc |
| ZERØAL | Calculate zero lift angle |
| ZERØGC | Set influence coefficient matrices to zero |

Description of the Subroutines Used in the Propeller Portion

Subroutine AFFIDC (ITØT, DECL, BØD, SCØ, AF, CLI, X, XB, R)

Object: To calculate the blade activity factor and integrated design lift coefficient.

List of Symbols

AF Blade activity factor
CLI Integrated design lift coefficient

Theory

The activity factor is defined as

$$AF = \int_{sco}^{1} \left(\frac{c}{D}\right) \left(\frac{x}{R}\right)^3 d\left(\frac{x}{R}\right)$$

where C/D is the blade chord to propeller diameter ratio and x is the spanwise location along the blades.

The integrated design lift coefficient is

$$CLI = 4(1-sco) \int_{sco}^{1} C_{\ell_d} \left(\frac{x}{R}\right)^2 d\left(\frac{x}{R}\right)$$

where SCØ is the root cutout and $C_{\ell d}$ is the section design lift coefficient.

Subroutine AF65A (Argument List)

Object Compute airfoil lift and drag from cascade correlations.

List of Symbols

Arugment List

| | | | | |
|---|---|---|---|---|
| AMACH | $M_1$ | , | Upstream Mach number | (INPUT) |
| ALP | $\alpha$ | , | Angle of Attack | (INPUT) |
| TM | t | , | Maximum Airfoil Thickness | (INPUT) |
| THETA | $\theta$ | , | Pitch angle | (INPUT) |
| CB | $C_B$ | , | Design Lift Coefficient | (INPUT) |
| SØLD | g/c | , | Cascade Solidity | (INPUT) |
| CL(1) | $C_L$ | , | Lift Coefficient | (OUTPUT) |
| CD(1) | $C_D$ | , | Drag Coefficient | (OUTPUT) |

Cascade Correlation

| | | | |
|---|---|---|---|
| ALPS | $\alpha_s$ | , | Stagger Angle (degrees) |
| ALP1 | $\alpha_1$ | , | Inlet Air Angle (degrees) |
| PHIC | $\phi_c$ | , | Camber Angle |
| AKDELS | $k_{\delta s}$ | , | Shape Parameters |
| AMSIG | $M_\sigma$ | , | Camber Parameter |
| B | b | , | Exponent |
| DEL | $\delta_{oo}$ | , | Deviation Angle, $\phi_c = 0$ |
| AKDELT | $K_{\delta t}$ | , | Thickness Parameter |
| DELO | $\delta_o$ | , | Deviation Angle (degrees) |
| AIOO | $i_{oo}$ | , | Incidence Angle, $\phi_c = 0$ (degeees) |
| AN | n | , | Power |
| AKIT | $K_{it}$ | , | Thickness Parameter |

| | | | |
|---|---|---|---|
| AIMO | $i_{mo}$ | , | Minimum Loss Incidence Angle (degrees) |
| D | D | , | Diffusion Parameter |
| ZLØSM | $Z_{sm}$ | , | Minimum Loss Coefficient |
| AINCO | i | , | Incidence Angle (degrees) |
| ZLØSS | $Z_s$ | , | Loss Coefficient |
| DALST | | , | Stall Angle Correction |
| ALPH2 | $\alpha_2$ | , | Exit Air Angle |
| RHØCX | $(\rho U_s)_2/(\rho U_s)_1$ | , | Mass Flow Ratio |

Additional Symbols

$(\alpha_2, Z_s) \rightarrow (C_L, C_D)$

| | | | |
|---|---|---|---|
| T1 | $T_{01}/T_1$ | , | Upstream Total Static Temperatures |
| AMACH2 | $M_2$ | , | Downstream Mach Number |
| T2 | $T_{02}/T_2$ | , | Downstream Total Static Temperature |
| PO2PO1 | $P_{02}/P_{01}$ | , | Total Pressure Ratio |
| P2P1 | $P_2/P_1$ | , | Static Pressure Ratio |
| FS | $F_S$ | , | Streamwise Force Coefficient |
| FP | $\underline{F}_p$ | , | Tangential Force Coefficient |
| WS | $W_s$ | , | Streamwise Induced Velocity |
| WP | $W_p$ | , | Tangential Induced Velocity |
| ALIND | $\alpha_i$ | , | Induced Flow Angle |
| ANG | $\alpha$ | , | Angle of Attack |

Theory — See section of reference 1 entitled: "Cascade Airfoil Data".

## Subroutine AIRFL

Object — Controls which type of airfoil data will be used, either isolated data or isolated data corrected for cascade effects.

Options

IDL $= 0$ print title
IDL $\neq 0$ obtain airfoil data
ICASDE $= 0$ obtain isolated airfoil data
ICASDE $= 1$ obtain isolated airfoil data corrected for cascade effects

Subroutine AIRFLT (IQ,IFQ,IDQ,ICASDQ,ALPHQ,THETAQ, TAUBQ,ZMQ,DECLQ,HØBQ,CL3Q,CDQ)

Object — Control combinations of airfoil data characteristics to be obtained.

Options

IDQ = 0 print title
IDQ = 1 obtain $C_L$ and $C_D$
IDQ = 2 obtain $C_L$ only

Subroutine AIRFMN (IC,IFL,I,NSTAT,RADCAS,RDTRAN, XMTIP,RSC,SMACH,THK,THETAG,DESCL,SIGMAX,TAU, ALP,CL,CD,FTRAN1,FTRAN2,TAUEXP)

Object — Control calculation of airfoil and cascade data and the interpolation between isolated and cascade data when requested.

Options

NG400 ≠ 0 use linearlzed airfoil data from aeroelastic response analysis (reference 12)

ICAS = 0 use isolated airfoil data

ICAS ≠ 0 use cascade data

If cascade data is used, interpolation between cascade data and isolated data is controlled by value of RDTRAN.

Argument List

| | |
|---|---|
| IC | controls lookup of $C_\ell$ alone or $C_\ell$ and $C_d$, or output of title information |
| IFL | airfoil type index |
| I | blade station index |
| NSTAT | blade station limit for tip loss model correction |
| RADCAS | outermost radial location for direct cascade data application |
| RDTRAN | outermost radial location for direct cascade/isolated airfoil interpolation procedure application |
| XMTIP | tip Mach number |
| RSC | radial station |
| SMACH | section Mach number |

| | |
|---|---|
| THK | section thickness ratio |
| THETAG | section geometric pitch angle with the plane of rotation |
| DESCL | section design lift coefficient |
| SIGMAX | section solidity |
| TAU | section gap to chord ratio |
| ALP | section angle of attack |
| CL | section lift coefficient |
| CD | section drag coefficient |
| FTRAN1 | section cascade/airfoil interpolation scaling function value for $C_\ell$ |
| RTRAN1 | section cascade/airfoil interpolation scaling function value for $C_d$ |
| TAUEXP | exponent used in interpolation function |

## Subroutine AIR23

Object: Calculate Manoni airfoil characteristics from internally tabulated data bank using transonic simularity rules.

Options:

IDL = 1 obtain $C_L$

IDL = 2 obtain $C_D$

IDL = 3 dummy feature

Theory:

Using transonic simularity rules, empirical data has been reduced to a set of tabulated coefficients which can be used to reconstruct the airfoil characteristics ($C_L$ and $C_D$) for a wide range of parameters.

## Subroutine AIR24

Object: Control selection of calculation of lift or drag coefficients for the published NACA data.

Options:

IDL = 1 obtain lift

IDL = 2 obtain drag

IDL = 3 dummy feature

### Subroutine ASSØC (*,S,FDUM,S1,S2,X)

Object — To transfer input value of a dummy parameter to its correct allocation if the input label matches one in the argument list. If transfer is made, returns to labeled statement in calling routine.

**Argument List**

| | |
|---|---|
| S | input label as read |
| FDUM | input dummy parameter |
| S1,S2 | input label list |
| X | allocation for transfer of dummy parameter |

### Subroutine AVECTR (A1,A2,A3,V)

Object — load three scalars into a vector of length three.

**Argument List**

| | |
|---|---|
| A1,A2,A3 | input scalars |
| V | output vector |

### Subroutine BILINE (T,I,XI,YI,Z,K)

Object — Bivariant or univariant interpolation on input vectors using various interpolation options.

Options

$T(I + 1) = 0$ use first table value

$T(I + 1) = 1$ use linear interpolation

$T(I + 1) = 2$ use third order interpolation

$T(I + 3) =$ non zero, requests bivariant interpolation

**Argument List**

T = vector with interpolation data
I = starting location for data table
XI = input x for interpolation
YI = input y for interpolation
Z = output value
K = error code

Theory

Using either bivariant or univariant data, this subroutine will interpolate on the data using standard interpolation schemes as noted above - see listing for more detail.

Subroutine BLDGEØ (IC)

Object — Rotate input lifting line segment geometry to the requested blade angle about the pitch axis and compute the inflow station geometry for this blade angle. Print the table of the lifting line segment and center coordinates.

List of Symbols

IC = print control flag

DRØØP = angle between the coordinate origin (hub center) and the axial displacement for the coordinate point in question for blade element center.

DRØØPB = angle between the coordinate origin (hub boundary) and the axial displacement for the coordinate point in question for the blade element boundary.

Theory — Standard geometric operations applied to the input geometry to rotate the coordinates to a different blade angle position.

Subroutine CALCGC (Argument List)

Object — To calculate the geometric influence coefficients for a selected field point in the cylindrical coordinate system.

Options

NCBWAK = 0 no compressibility effects on the bound vortex induced velocity calculation

NCBWAK = 1 compressibility effects included on the bound vortex induced velocity calculations

NCBWAK = 2 compressibility effects included in the bound vortex induced velocity calculation, except for the calculation for the particular blade bound vortex system on itself

IJUNK = 0 no vortex core model

IJUNK = 1 vortex core model used

IDEBUG = 0 no intermediate printout

IDEBUG = 1 intermediate printout

NCØMPRS = 0 no wake compressibility model

NCØMPRS = 1 wake compressibility model used

NCFLØW = 0 wake compressibility applied only on vortex segments from inflow sections with Mach numbers greater than 1.0

NCFLØW = 1 relaxes the above restriction

<u>Argument List</u>

NCØMP = compressible wake option switch
IBIP = blade index
LLINK = blade position index
NBX = number of blades
ITØT = number of blade element segments
LTØT = number of blade positions
KTØT = number of blade element boundaries
MTØT = number of filament segments
KTRUCT = number of filaments for tip vortex rollup model
JTRUCT = wake rollup truncation angle
JTRUCI = inboard wake truncation angle
DPSIBR = azimuth interval in radians
FS = sign (±1.0) for axial induced velocity calculation
RSCI = radial location of field point
PHICI = lag angle of field point
ZSCI = axial location of field point
CPD = cosine of blade element angle
SPD = sine of blade element angle
RSBB = blade element boundary radial position
ZSBB = blade element boundary axial position
PHIBB = blade element boundary azimuth position
CØSLB = blade element boundary cosine of azimuth position
SINLB = blade element boundary sine of azimuth position
CMACH = local blade element Mach number
MU = local blade element advance ratio
DTIPM = blade tip Mach number
VØRCØR = vortex core radius

**Theory** Using the Biot-Savart relationship for the geometric influence coefficients for straight line vortex segments (see Appendix A of reference 1), these coefficients are calculated, summed and stored in cylindrical system form. See the technical approach for the propeller analysis in reference 1.

## Subroutine CALWAK (IWK)

**Object** Control selection of wake models

**Options**

IWAKØP = 0 classical wake geometry
IWAKØP = 1 classical wake geometry
IWAKØP = 2 input geometry
IWAKØP = 3 generalized wake geometry
NACWAK ≠ 0 modify wake geometry by nacelle influence
IPRØPT ≠ 0 print wake geometry

## Subroutine CASARF

**Object** Controls the calculation procedure for the computation of the isolated airfoil data corrected for cascade effects.

**Options**

IDL = 1 calculate $C_L$ and correct for cascade influence
IDL = 2 calculate $C_D$
IDL = 3 dummy feature

**List of Symbols**

CLKFAC = cascade correction scaling factor

THETAZ = geometric blade angle corrected for camber and angle of zero lift

**Theory**

The lift coefficient is corrected for cascade effects by applying an analytical correction for the cascade influence on flat plates. The details of this correction are presented in reference 1.

## Subroutine CASDAT (Argument List)

<u>Object</u> Control selection of cascade data source.

<u>Options</u>

ICAS = 0 terminate execution of code
ICAS = 1 cascade data using correlation from reference 13
ICAS = 2 cascade data using model of reference 11

<u>Argument List</u>

| | | |
|---|---|---|
| ICAS | = | option switch for type of cascade data |
| MACH | = | local section Mach number |
| AL | = | local section angle of attack |
| THK | = | local section thickness ratio |
| THET | = | local section blade angle |
| DESCLP | = | local section design lift coefficient |
| SIG | = | local section solidity ratio |
| CL | = | local section lift coefficient |
| CD | = | local section drag coefficient |

## Subroutine CHKINP

<u>Object</u> To check input data for correct input values on selected items and make sure items that are necessary for successful execution are input.

## Subroutine CLFACT (THETA,TAUB,CLKFAC)

<u>Object</u> Obtain tabled value of lift curve slope scaling factor for input parameters.

<u>List of Symbols</u>

| | | |
|---|---|---|
| THETA | = | geometric blade angle corrected for camber and angle of zero lift |
| TAUB | = | gap-to-chord ratio |
| CLVFAC | = | lift curve slope scaling factor |

<u>Theory</u> Table of data for the lift curve slope scaling factor was derived analytically for flat plates by Weinig. The table of data was obtained from reference 4.

## Subroutine CØMBWK (Argument List)

<u>Object</u> To compute an effective axial displacement correction on the bound vortex location for incorporating the phase shift of the induced influence of the bound wake on an inflow station.

<u>Argument List</u>

RA = radial location of the midpoint of a bound vortex segment
RB = radial location of the inflow station
DZ = axial location of a bound vortex segment
MU = flight speed divided by tip speed
DTIPM = tip Mach number
DPSI = azimuthal position of bound vortex segment
Z = effective axial displacement
PHI = effective phase angle

<u>Theory</u> The first real positive root of a transcendental equation is solved by a simple root searching algorithm and a Newton-Raphson iteration procedure. This root represents an effective phase angle associated with the finite delay time for a signal to reach an inflow station point if it originally emanated from a bound vortex source inside a zone of silence of a Mach cone.

## Subroutine CPITER (Argument List)

<u>Object</u> To calculate either a first guess on blade angle or subsequent iterations values for the blade angle when the power performance iteration feature is requested.

<u>Options</u> NCP = 1 obtain first guess from tabled values

NCP = 2 obtain second value from one of two methods

NCP = 3,...,10 obtain all subsequent values by linear interpolation or extrapolation from previous iteration information

DPDT = 0.0 for NCP = 2 use a new blade angle of ±1.5 degrees from the first iteration value

DPDT ≠ 0.0 for NCP = 2 use DPDT as the linear slope to define the next blade angle

Argument List

| | | |
|---|---|---|
| ITØT | = | number of blade elements |
| BL | = | number of blades |
| ZJI | = | advance ratio |
| RSC | = | inflow station segment radial centers |
| RSB | = | inflow station boundary radial locations |
| DESCL | = | design lift coefficient |
| BØD | = | chord over diameter ratio |
| CPWANT | = | requested power coefficient |
| DPDT | = | input linear slope of the power coefficient versus blade angle relationship |
| RAD | = | blade radius |

Theory

Using standard interpolation and extrapolation techniques, the blade angle for each iteration of the power performance iteration is determined. For the first iteration tabled values are used if requested and for the second iteration one of two methods can be used to determine the new blade angle. All subsequent iteration values are obtained using linear extrapolation or interpolation based on previous iteration information.

Subroutine CRØSSP (V,A,R1,R2,R3)

Object

Calculate cross product of two vectors and place results in three scalars.

Subroutine CSCD1 (IND,CB,TH,SOL,ST,RN,AM,ILF,SLF,CL,CD)

Object — Calculate cascade lift and drag coefficients from reference 13.

Argument List

IND = controls selection of airfoil type
CB = section camber
TH = section thickness ratio
SØL = section solidity
ST = section pitch angle
RN = Reynolds number (fixed at 500000)
AM = section angle of attack
CL = section lift coefficient
CD = section drag coefficient

Subroutine CTITER (CTWANT,DCTDT)

Object — To calculate either the first or all subsequent blade angles when the thrust iteration has been requested.

Options

NCP = 1 use a fixed value of 60.0 degeees for the first guess
NCP = 2 use one of the two methods to determine the second value

NCP = 3,..,10 use linear interpolation or extrapolation based on the previous iterations to determine the next value

DCTDT = 0.0 for NCP = 2 use a new blade angle of ±1.5 degrees from the first iteration value

DCTDT ≠ 0.0 for NCP = 2 use the value of DCTDT as the linear slope to define the next blade angle

Theory — Using standard interpolation and extrapolation techniques, the blade angle for each iteration of the thrust iteration cycle is determined. For the first iteration, a fixed value is used if requested and for the second iteration one of two methods can be used to determine the new blade angle. All subsequent iterations values are obtained using linear interpolation or extrapolation based on previous iteration information.

Subroutine DØTP (V,A)

Object — Calculate dot product of two vectors, each of length three.

## Subroutine DRAG24

<u>Object</u> Calculate drag coefficient from the NACA airfoil data.

<u>Theory</u> Using linear interpolation techniques applied to a set of tabulated airfoil drag coefficients which are functions of Mach number, angle of attack, thickness to chord ratio and design lift coefficient, the drag coefficient is found for a specified combination of the above parameters (reference 1).

## Subroutine DZRØAL (THSTAR,TAUB,THETAT,DELAØL)

<u>Object</u> Determine increment in angle of zero lift for cascade correction procedure.

<u>Argument List</u>

THSTAR = effective blade camber angle
TAUB = gap-to-chord ratio
THETAT = effective blade angle
DELAØL = increment in angle of zero lift

<u>Theory</u> Using trivariate interpolation techniques, the increment in the angle of zero lift is determined from a set of tabulated data for double circular arc aifoils (reference 5).

## Subroutine ELIP2 (X)

<u>Object</u> Calculate approximation for elliptic integral of the second kind.

<u>Argument List</u>

X = argument of approximation function

## Subroutine FINAIR

<u>Object</u> Control final calculation procedure for airfoil characteristics.

<u>Options</u>

| | | |
|---|---|---|
| IDEBUG | = 0 | no printout |
| IDEBUG | > 0 | printout of final values for the airfoil characteristics is requested |
| ICAS | = 0 | no cascade airfoil data is used |
| ICAS | ≠ 0 | cascade airfoil data is used out to a requested radial location |

## Function FSQRT (X,Y,Z)

Object — Calculate magnitude of vector of components X, Y, and Z

Theory — $FSQRT = (X^2 + Y^2 + Z^2)^{1/2}$

Argument List

X,Y,Z = components of vector
FSQRT = resultant

## Subroutine FVECTR

Object — Calculate components of blade forces at each blade inflow station.

Options — IDEBUG ≠ 0 request printout of component forces

List of Symbols

ALFLC = lift force in the chordwise direction
ALFLN = lift force in the normalwise direction
ALFLS = lift force in the spanwise direction
ALFDC = drag force in the chordwise direction
ALFDN = drag force in the normalwise direction
ALFDS = drag force in the spanwise direction

Theory — Using a calculated blade section lift and drag coefficients and the appropriate aerodynamic quantities, the forces in the blade element coordinate system are calculated and these forces are transformed to the cylindrical coordinate system.

## Subroutine GAUSS (Augument List)

Object — Solve a system of simultaneous linear equations in matrix form using a direct solution technique.

Argument List

NRØWM = row dimension of the coefficient matrix
N = number of rows and columns used in the matrix solution
A = coefficient matrix
B = constant vector and on output contains the solution vector

DET = mantissa of the value of the determinant in base ten
IDET = integer power to the base ten of the determinant
LSING = singularity flag

Theory — Using a standard Gauss-Jordan reduction method a system of simultaneous linear equations is solved and the determinant of the matrix is calculated.

Subroutine GCBØUN (RSC,CP,SP,ZSC,RSB,ZSB,PHIB, CØSLB,SINLB,CMACH,MU,TIPM,VCØR)

Object — Calculate geometric influence coefficients at a specified load point for the bound vortex segments which represent the propeller blade lifting line.

Argument List

RSC = radial position of load point at which induced influence is to be calculated
CP = cosine of azimuthal position of load point
SP = sine of azimuthal position of load point
ZSC = axial position of load point
RSB = radial location of bound vortex segment endpoints
PHIB = azimuthal position of bound vortex segment endpoints
CØSLB = cosine of azimuthal position of bound vortex segment endpoints
SINLB = sine of azimuthal position of bound vortex segment endpoints
CMACH = mach number of bound vortex segment endpoints
MU = advance ratio of propeller disk
TIPM = tip mach number of propeller disk
VCØR = vortex core radius

Theory — Uses the potential flow solution for the induced influence of a finite length straight vortex filament, formulated in a cylindrical coordinate system. See Appendix B, Volume I.

Subroutine GCCØRE (IB,IFILA,IDEBUG,IFLAG,RARB,
ZAZB,RASQ,RBSQ,CP,DSCA,DSCA,VCØR)

Object — Tabulate induced influence of a vortex segment if the load point is within the core radius.

Argument List

IB = type of vortex segment indicator (bound or trailing)
IFILA = vortex segment number
IDEBUG = debug output trigger
IFLAG = flag

RARB = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

ZAZB = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

RASQ = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

RBSQ = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

CP = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

DSCA = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

DSCA = intermediate geometric quantity needed for the calculation, see Appendix B, Volume I

VCØR = vortex core radius

Theory — If the load point at which the induced influence due to a vortex segment is within a specified core radius, the induced influence is modeled by a solid body rotation model. This removes the singular behavior due to a purely potential flow vortex.

Subroutine GCFILA (K,NCØMPT,IBIWK,LBTØT,LLIWK,
RSCI,CP,SP,ZSCI,KTRUCT,JTRUCT,JTRUCI,MTØT,KTØT,
LTØT,CØSLB,SINLB,DTIPM,VØRCØR)

Object — Calculate geometric influence coefficients at a specified load point for the trailing vortex segments of a specified filament which represent the wake geometry.

Options

| | | |
|---|---|---|
| NCØMPT | = 0 | no compressible wake |
| NCØMPT | ≠ 0 | use compressible wake |
| KTRUCT | ≠ 0 | wake rollup model used beyond this filament index value |
| VØRCØR | ≠ 0 | vortex core option requested |

Argument List

| | |
|---|---|
| K | = vortex filament index |
| NCØMPT | = option control for compressible wake model |
| IBIWK | = blade index for wake |
| LBTØT | = blade and rotor position index |
| LLIWK | = rotor position index of wake |
| RSCI | = radial position of load point |
| CP | = cosine of azimuthal position of load point |
| SP | = sine of azimuthal position of load point |
| ZSCI | = axial coordinate of load point |
| KTRUCT | = filament index defining boundary for tip vortex rollup model |
| JTRUCT | = filament azimuth position index for wake truncation associated with tip rollup model |
| JTRUCI | = filament azimuth position index for wake truncation for inboard wake |
| MTØT | = number of segment endpoints |
| KTØT | = number of filaments |
| LTØT | = number of rotor positions |
| CØSLB | = cosine of filament azimuth position at blade |
| SINLB | = sine of filament azimuth position at blade |
| DTIPM | = reciprocal of blade tip Mach number |
| VØRCØR | = vortex core radius |

Theory — Uses the potential flow solution for finite length straight vortex segment, formulated in a cylindrical coordinate system. See Appendix B, Volume I.

## Subroutine GCWAKE

Object — Controls flow of the geometric influence coefficient calculations. A flow diagram is presented in figure 12.

Options

IWAKØP = 0 standard wake model (modified classical wake)
IWAKØP = 1 classical wake model
IWAKØP = 2 input wake geometry
IWAKØP = 3 generalized wake model
NACWAK ≠ 0 obtain nacelle corrections for wake geometry
IPRØPT ≠ 0 print wake geometry

## Subroutine G400LD (I,ALPHA,CL,CD)

Object — Calculate lift and drag airfoil characteristics obtained from an external source.

Argument List

I = blade segment index
ALPHA = section angle of attack
CL = section lift coefficient
CD = section drag coefficient

Theory — The lift and drag characteristics for each blade element segment are obtained from an external source by curve fitting a quadratic polymonial about the angle of attack at each station. The lift and drag are reconstructed in this subroutine for use in the solution procedure.

## Subroutine INDVEL

Object — Compute induced velocities.

Option — IDEBUG ≠ 0 print the calculated induced velocities

Theory — Reading the stored geometric influence coefficients in a defined order from a disc, the induced velocities are calculated by multiplying and summing over the appropriate indices of the matrix quantities.

## Subroutine INTIAL

Object — To calculate selected data and printout initial input data.

## Subroutine ISØAFL

Object — Control selection of type of isolated airfoil data tables to use (Manoni or NACA).

Options —
IDL = 1 lift only
IDL = 2 drag
IDL = 3 dummy feature
IFL = 23 use Manoni data
IFL = 24 use NACA data
IFL < 23 or > 24 use Manoni data

## Subroutine ISØARF

Object — Control the flow of isolated airfoil data module.

Options —
IDL = 0 return to calling routine
IDL = 1 compute lift
IDL = 2 compute drag

## Subroutine LDDATA

Object — Read in required initial propeller input data and calculate selected data from input quantities.

## Subroutine LIFT24

Object — Calculate lift coefficient from tabulated airfoil data tables containing the NACA data.

Theory — Using linear interpolation techniques this subroutine computes the lift coefficient from a table of NACA airfoil data which is a function of Mach number, angle of attack, design lift coefficient and thickness to chord ratio (reference 1).

## Subroutine LINEAR (Argument List)

<u>Object</u>   Interpolate and extrapolate linearly on an input set of data.

<u>Argument List</u>

NW = print output file number
N = number of data points in the interpolation vectors
XIN = independent data vector
YIN = dependent data vector
XØUT = requested interpolation point
YØUT = interpolated value
LØFF = interpolation flag

<u>Theory</u>   Simple linear interpolation algorithm; if off scale on the low or high end, the flag is set (1 or 2 respectively) and the boundary slope is used to extrapolate to the requested interpolation point.

## Subroutine LINTER (Argument List)

<u>Object</u>   Control the interpolation of selected data arrays from input interpolation tables.

<u>Options</u>   NERR = 1 use lower boundary value
NERR = 2 use upper boundary value

<u>Argument List</u>

N = number of data points in the interpolation vector
K = number of requested interpolation points
XIN = independent interpolation vector
YIN = dependent interpolation vector
X = vector of requested interpolation points
Y = vector of interpolated values

Subroutine MCØNE (Augument List)

<u>Object</u> Calculate Evvard Tip Relief Correction.

<u>Options</u>

NEVARD = 0 no correction
NEVARD = 1 used tabled values
NEVARD = 2 use equation

<u>Argument List</u>

NEVARD = option control for method of calculation
IP = propeller index
L = propeller position index
RSC = radial location of inflow station
C = chord
R = propeller radius
ITØT = number of inflow stations
CNSECT = fraction of chord
XMTIP = tip Mach number
NSTAT = station index for boundary for Mach cone intersection
XKCØNE = tip relief correction vector
RTIP = tip radius

<u>Theory</u> See section of reference 1 entitled: "Evvard Tip Relief for Propellers".

Subroutine MVMULT (V,M,R1,R2,R3)

<u>Object</u> Multiply a three by three matrix by a vector of length three. Store the result in three separate scalars.

<u>Argument List</u>

V = vector
M = matrix
R1,R2,R3 = resultant scalars

## Subroutine NSTACØ (Argument List)

Object — Calculate Mach Cone intersection station index.

Options — IDEBUG > 0 requests printout of selected data

Argument List

NSTAT = station index where intersection occurs
XMTIP = tip Mach number
IP = propeller index
L = propeller position index

Theory — Using relative geometry the angle XNETA is computed for each station and compared with the Mach cone angle, BETA, until the station where the intersection of the Mach cone with the specified fraction of the blade chord is determined.

## Subroutine PAGE (NWRITE)

Object — Print new page.

Argument List

NWRITE = print output file number

## Subroutine PCHØUT (NUNIT)

Object — Output spanwise distributions of aerodynamic and geometric quantities to specified output device number.

Argument List

NUNIT = output file number

## Subroutine PERFØR

Object — Compute and print out the propeller performance parameters.

Theory — Uses standard integration techniques to obtain the integrated thrust and power from the blades force components in the cylindrical coordinate systems.

$$\text{Thrust} = \int_{\text{Root}}^{\text{Tip}} F_z c\,dr \qquad \text{Torque} = \int_{\text{Root}}^{\text{Tip}} F_\phi r c\,dr$$

where

$c$ = chord
$F_z$ = axial force per unit area
$F_\phi$ = tangential force per unit area
$r$ = local blade radius

## Subroutine PERIØD

Object — Calculate propeller disc periodicity and related quantities.

Theory — For single propeller disc configurations, the geometric relationship between the wake and blades is fixed. However, for a coaxial propeller, the geometric relationships are periodic with half-blade spacing if the number of blades and rotational speeds are equal. For unequal blades and/or unequal rotational speed, the relationship defining the periodicity (t) of the wake and blade geometry is

$$t = \frac{2\pi}{b_{max}(\Omega_1 + \Omega_2)}$$

where $\Omega_1$ and $\Omega_2$ are the rotational speeds of the two propellers, and $b_{max}$ is the maximum number of blades of the two propellers.

Subroutine PERPRT (NW,L,IP)

Object — Print spanwise distributions of aerodynamic and geometric quantities to a specified output unit.

Argument List

NW = output unit number
L = propeller position index
IP = propeller index

Subroutine PHICAL (MTØT,DPSI)

Object — Compute wake azimuth positions and trigonometric relationships for all propeller azimuth positions.

Argument List

MTØT = number of wake filament segments
DPSI = azimuthal increment

Theory — Using the requested blade azimuth increment, the wake azimuth position and the sine and cosine functions for such are computed and stored. The fact that the sine and cosine functions are periodic is made use of to reduce the actual number of sine and cosine values which are stored.

Subroutine PLABEL (NWRITE,NSLB,NSLF,NSP,NL,LABEL)

Object — Print a label field.

Argument List

NWRITE = output device number
NSLB = number of lines to skip before label is output
NSLF = number of lines to skip after label is output
NSP = number of units of 10 spaces to skip before label is output
NL = length of label in increments of 6
LABEL = label vector

Function PN (N,R,S)

<u>Object</u> Compute special functions of R and S.

<u>Options</u>

| | |
|---|---|
| N = 0 | PN = 1 |
| N = 1 | PN = 1 / (R-S) |
| $N \geq 2$ | PN = $R^{N-2}$ |

Subroutine PRØP

<u>Object</u> Control sequencing of propeller lifting line solution procedure. A flow diagram is presented in figure 13.

<u>Options</u>

CPI ≠ 0 requests power iteration (overrides thrust iteration)
CTI ≠ 0 requests thrust iteration

Subroutine PRDATA (T,IUNIT,N,X)

<u>Object</u> Output label vector and floating point vector to specified output unit number using 7A6/8E10.4/8E10.4 format.

<u>Argument List</u>

T = label vector
IUNIT = outut unit number
N = length of floating point vector
X = floating point vector

## Subroutine PRG400

Object

Output required velocity quantities to specified unit number in a format compatible with an aeroelastic response analysis (reference ~~22~~).
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## Subroutine PRINTP (NWRITE,IFCØDE,N,FDATA,LABEL)

Object

Output label vector and floating point vector with specified format of form 7A6,10F9.X.

Argument List

NWRITE = output unit number
IFCØDE = format code index
N = length of floating point vector
FDATA = floating point vector
LABEL = label vector

## Subroutine PRTF15 (NWRITE,IFCØDE,N,FDATA,LABEL)

Object

Output label vector and floating point vector of specified length to a specified unit number using a format of form 3A6,15F8.X.

Argument List

NWRITE = output unit number
IFCØDE = format code index
N = length of floating point vector
FDATA = floating point vector
LABEL = label vector

## Subroutine PRTF16 (NWRITE,IFCØDE,N,FDATA,LABEL)

Object

Output label vector and floating point vector of specified length to a specified unit number using a format of form 3A6,16F7.X.

Argument List

NWRITE = output unit number
IFCØDE = format code index
N = length of floating point vector
FDATA = floating point vector
LABEL = label vector

## Subroutine PRTGCM (NWRITE,IØP,NRØW,NCØL,GCMAT)

Object — Output two-dimensional influence coefficient matrix to specified unit number, in one of two formats.

Argument List

NWRITE = output unit number
IØP = format option index
NRØW = row dimension of matrix
NCØL = column dimension of matrix
GCMAT = matrix

Options — IØP = 0 use format 15F8.5
IØP = 1 use format 15F8.3

## Subroutine PRTI15 (NWRITE,N,LABEL)

Object — Output to specified unit number a label and integer index with format of form 2A6,I7,14I8.

Argument List

NWRITE = output unit number
N = length of integer index
LABEL = label vector

## Subroutine PRTI16 (NWRITE,N,LABEL)

Object — Output to specified unit number a label vector and integer index with format of form 3A6,I6,15I7.

Argument List

NWRITE = output unit number
N = length of integer index
LABEL = label vector

Subroutine PRTLF (NWRITE,F,LABEL)

Object — Output label vector and single floating point scalar with format of form 5A6,F15.5.

Argument List

NWRITE = output unit number
F = floating point scalar
LABEL = label vector

Subroutine PRTLI (NWRITE,N,LABEL)

Object — Output label vector and single integer value with format of form 5A6,I10.

Argument List

NWRITE = output unit number
N = integer value
LABEL = label vector

Subroutine PRTRZW (NWRITE,RSB,PHI,RZW,MTØT,KTØT,IRZ)

Object — Output floating point vectors to specified unit number with integer indices with specified format.

Options — IRZ = 0 use format of form 16F7.3
IRZ = 1 use format of form 16F7.2

Argument List

NWRITE = output unit number
RSB = floating point vector
PHI = floating point vector
RZW = floating point vector
MTØT = length of column vector
KTØT = length of row vector
IRZ = option for format type

Subroutine PRWZW (RSBB)

<u>Object</u> Control print of wake coordinates.

<u>Argument List</u>

RSBB = blade element segment boundary radius

Subroutine RDSCAL (IVPRNT)

<u>Object</u> Read scalar input parameters necessary to run program.

<u>Options</u> NG400 ≠ 0 read data from external unit source for necessary scalar input for coupling with aeroelastic response analysis (reference 12)

<u>Argument List</u>

IVPRNT = print option for vector input listing

Subroutine RDVECT (IVPRNT)

<u>Object</u> Read vector inputs necessary to run.

<u>Options</u> IVPRNT ≠ 0 no listing of inputs as read in
NG400 ≠ 0 read vector inputs from external source for coupling with aeroelastic response analysis (reference 12)

<u>Argument List</u>

IVPRNT = option flag to terminate listing of input vector as read in

### Subroutine READWR (*,NREAD,NWRITE,IT,S,ST,X)

<u>Object</u> Read input vectors if label fields match.

<u>Argument List</u>

| | | |
|---|---|---|
| * | = | return 1 |
| NREAD | = | input unit number |
| NWRITE | = | output unit number |
| IT | = | length of vector |
| S | = | input label field |
| ST | = | test label field |
| X | = | input vector |

### Subroutine RELAXG (ITER,ICØV,RELAXF,GAMMA)

<u>Object</u> Relaxation of circulation solution and convergence flag set in this subroutine.

<u>Argument List</u>

| | | |
|---|---|---|
| ITER | = | iteration index |
| ICØV | = | convergence flag |
| RELAXF | = | relaxation factor |
| GAMMA | = | temporary single dimension variable for solution storage |

<u>List of Symbols</u>

| | | |
|---|---|---|
| CIRC | = | current circulation stored in this matrix |
| SAVCIR | = | previous iteration circulation stored in this matrix |

### Subroutine REDMAT (Argument List)

<u>Object</u> Read all geometric influence coefficients from disk and create the geometric influence coefficient matrix.

<u>Argument List</u>

| | | |
|---|---|---|
| NM | = | dimension for the maximum number of rows in the matrix |
| MSIZE | = | number of rows used in the matrix |
| GCN | = | geometric influence coefficient matrix |

## Subroutine RWZWIN (IWK)

Object    Input wake geometry coordinates.

List of Symbols

PHI = wake azimuth position
RW = radial coordinates of wake
ZW = axial coordinates of wake
IWK = wake index number

## Subroutine RWZW1 (IWK)

Object    Compute wake coordinates for classical or modified classical wake model.

Options    IWAKØP = 0    use prescribed inflow distribution and the momentum induced velocity to define the wake geometry (modified classical wake)

IWAKØP = 1    use the freestream velocity and the momentum induced velocity to define the wake geometry (classical wake)

List of Symbols

PHI = wake azimuth position
RW = radial coordinates of wake
ZW = axial coordinates of wake
IWK = propeller wake index number
VWAKE = propeller wake transport velocity

Theory    Classical wake.

VWAKE = -VKTAS*1.688+VIMØM

Modified classical wake

VWAKE = VZERØB(I)+VIMØM

## Subroutine RWZW7 (IWK)

Object — Compute generalized wake geometry.

Options
- IØPT = 0 — linear fit for wake geometry between tip filament and non-rolled up filaments outboard of the outer sheet filament
- IØPT = 1 — parabolic fit for filaments as noted above

List of Symbols

PHI = wake azimuth position
RW = radial coordinates of wake
ZW = axial coordinates of wake
IWK = wake index number

Theory — See reference 1.

## Function SBFUNC (X)

Object — Calculate value of special function.

Argument List

X = specified independent parameter
SBFUNC = function value for specified X

Theory — A special function for the stall bucket (reference 11) is tabulated for interpolation on the independent parameter X. Beyond the range of tabulated data, the following function is used.

$$SBFUNC = e^{X}-2.139$$

## Subroutine SETMAT

Object — Read from a disk in a specified order the geometric influence coefficients and combine them on another disk for the matrix solution algorithm.

List of Symbols

NPRØP = number of propellers
LTØT = number of propeller positions
ITØT = number of inflow stations
MSIZE = matrix row size
GCC = chordwise influence coefficients
GCN = normalwise influence coefficients
GCS = spanwise influence coefficients

## Subroutine SØLVEL

Object — Calculate required quantities associated with the propeller aerodynamics and control the linearized solution procedure. A flow diagram is presented in figure 14.

Options

| | | |
|---|---|---|
| IDEBUG | $\neq 0$ | print out intermediate quantities |
| NEVARD | $\neq 0$ | use Evvard Tip Relief Correction |
| ICAS | $\neq 0$ | use cascade airfoil data inboard of requested radial station |
| IPRMAT | $\neq 0$ | print matrix related quantities |
| MATSØL | $= 0$ | use direct matrix solution technique |
| MATSØL | $= 1$ | use iteration matrix solution technique |
| INPT | $\neq 0$ | print circulation solution |

Theory — See section entitled: "Linearized Aerodynamics" of reference 1.

## Subroutine SØLVEN

Object — Calculate required quantities for propeller aerodynamics and control the nonlinear matrix solution procedure. A flow diagram is presented in figure 15.

Options

| | | |
|---|---|---|
| ICAS | $\neq 0$ | use cascade airfoil data inboard of requested radial solution |
| IPNT | $\neq 0$ | print intermediate circulation solutions |
| MATSØL | $= 0$ | use direct matrix solution technique |
| MATSØL | $= 1$ | use iterative matrix solution technique |
| IDEBUG | $\neq 0$ | print out intermediate quantities |

Theory — See section entitled: "Nonlinear Aerodynamics" of reference 1.

## Subroutine SØLVIT

Object — Control flow of solution procedure.

Options — ITYPES = 0 linear aerodynamic solution only
ITYPES = 1 nonlinear aerodynamic solution

## Subroutine SPLIN3 (Argument List)

Object — Interpolate using spline fit.

Options — NWØT = controls calculation of derivatives

Argument List

XDATA = independent interpolation variable vector
YDATA = dependent interpolation variable vector
NDATA = number of interpolation table data points
XIN = vector of requested interpolation table data points
YØUT = interpolation values at the interpolation points
YPRIME = vector of derivatives at the interpolation points
NXY = number of requested interpolation points
NWØT = option control on derivatives

Theory — Standard spline fitting technique.

## Subroutine STARC (Argument List)

Object — Convert design lift coefficient to equivalent camber angle.

Argument List

DECL = design lift coefficient
THSTAR = effective camber angle

Theory — Using second order interpolation technique on a prestored table of data, the design lift coefficient is converted to the equivalent camber angle for a double circular arc airfoil.

Subroutine STØRE (I,J,K,X,Y)

Object Store the vector X into the vector Y where X and Y can be externally dimensioned as three dimensional arrays.

Argument List

I,J,K = dimension limits of the X and Y arrays
X = input vector (array)
Y = output vector (array)

Function SWPCØR (S,CØ,MACH,LAMLE,LAMTE,Y)

Object Calculate tip loss factor for propeller blade using conical flow theory.

Argument List

S = semispan of wing which is used to approximate swept propeller tip
CØ = midspan chord of wing
MACH = Mach number
LAMLE = leading edge sweep angle
LAMTE = trailing edge sweep angle
Y = spanwise position on wing measured from midspan
SWPCØR = scaling result

Theory Concial flow theory for a thin sweep wing with subsonic leading edge and supersonic trailing edge is used to obtain the three-dimensional section $C_\ell$. This solution is divided by the equivalent thin wing two-dimensional solution to obtain a scaling function to apply to actual two-dimensional tabulated $C_\ell$ data.

## Subroutine THITER

<u>Object</u> Control selection of $C_p$ or $C_T$ blade angle iteration.

## Subroutine TITER (N,T,DQDT,QWANT,QCALC,TØL,IQØK)

<u>Object</u> Linearly interpolate or extrapolate on input vector to obtain required T at requested Q.

<u>Argument List</u>

N = iteration index
T = output vector
DQDT = initially assumed slope of Q versus T curve
QWANT = requested Q
QCALC = input Q vector
TØL = tolerance or solution
IQØK = iteration control flag

## Subroutine UNBAR (Argument List)

<u>Object</u> Bivariant Interpolation on data vector.

<u>Argument List</u>

T = table of bivariant interpolation data (Z vs. X and Y)
IK = starting location of data
XIN = requested interpolation point (X)
YIN = requested interpolation point (Y)
ZZ = interpolated value
KK = interpolation flag

<u>Theory</u> Use standard bivariant interpolation algorithm with degree choice internally coded.

## Subroutine UNINT (Argument List)

Object — Univariant interpolation.

Argument List

NW = print output file number
N = number of interpolation data points
XA = vector of independent interpolation data
YA = vector of dependent interpolation data
X = requested interpolation point
Y = resulting interpolated data values
Z = interpolation flag

Theory — Interpolates over a four point interval using a variation of a 2nd degree interpolation to produce a continuity of slope between adjacent intervals.

## Subroutine VECTØR

Object — Compute velocity related quantities required for propeller aerodynamics.

Options — IDEBUG ≠ 0 printout of selected intermediate quantities

Theory — Using vector algebra, the direction cosines of the local velocity vectors at the blade are calculated neglecting induced velocity terms, along with other related quantities.

## Subroutine VVECTR

Object — Compute velocity related quantities for the propeller aerodynamics.

Options — IDEBUG = 0 printout intermediate quantities.

Theory — Using vector algebra, the direction cosines of the local velocity vectors at the blade are compiled including effects along with other related velocity quantities.

## Subroutine WAKMØD (KTØT,MTØT,IDEBUG)

Object — Read wake displacement corrections from disk and modify the internally calculated wake geometry.

Options — IDEBUG ≠ 0 printout selected quantities

List of Symbols

| | | |
|---|---|---|
| PHI | = | wake azimuth position |
| RW | = | radial wake coordinate |
| ZW | = | axial wake coordinate |
| KTØT | = | number of wake filaments per blade |
| NTØT | = | number of wake revolutions |
| JTØT | = | number of wake azimuth positions per wake revolution |
| JTØT1 | = | JTØT+1 |
| IDEBUG | = | print option |

Theory — See section entitled: Nacelle Influence on Wake Geometry of reference 1.

## Subroutine WRITGC (Argument List)

Object — Convert vectors of geometric influence coefficients to the blade coordinate system in the order in which they are calculated and write them to disk for later retrieval.

Options — IPRMAT ≠ 0 printout geometric influence coefficients

Argument List

| | | |
|---|---|---|
| IX | = | local blade station index specifying the particular blade element station to transform the influence coefficients vectors from cylindrical to blade element coordinate system |
| LL | = | propeller position index |
| IWK | = | propeller wake index |
| IBB | = | blade index |
| IP | = | propeller index |
| IWRITE | = | disk number to write influence coefficients onto |

Theory — Standard geometric transformation applied to the cylindrical coordinate system influence coefficients to transform them to blade element coordinate system, before storing the disk for later retrieval.

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## Subroutine ZERØGC (MK,N2,N3,GC)

Object Set an externally dimensioned three dimensional array to zero.

Argument List

MK,N2,N3 = external dimensions of array GC
GC = input array

## Subroutine ZERØAL (THSTAR,APZL)

Object Calculate angle of zero lift for isolated airfoils.

Argument List

THSTAR = effective camber angle
APZL = angle of zero lift

Theory The angle of zero lift is calculated for the requested isolated airfoil type by computing the linear lift curve slope near zero angle of attack and solving for the intercept of the straight line with the resultant linear lift curve slope.

## Labeled Common Blocks used in the Propeller Portion

Included herein is a list of the labeled common blocks in alphabetical order used in the propeller portion of the analysis and a description of each variable used in them (NDN designates a non-dimensional number).

| Common Block Name (Object) | Variable Names | Description of Variables |
|---|---|---|
| AERDAT (Store Miscellaneous Aerodynamic Quantities) | | |
| | AA | Linearized lift curve slope (per radian) |
| | DIAG | Diagonal element vector of geometric influence coefficient matrix (per ft.) |
| | CØNST | Constant vector of circulation solution matrix ($ft^2/sec$) |
| | CMACH | Local total Mach number (NDN) |
| | SMACH | Local section Mach number (NDN, normal to lifting line) |
| | CFDP | Constant vector correction term ($ft^2/sec$) |
| | SKEW | Aerodynamic skew angle (degrees) |
| AFDATX (Store Isolated Airfoil Data Package Quantities) | | |
| | I | Inflow station index |
| | IFL | Airfoil type flag |
| | IDL | $C_L$, $C_D$ calculation flag |
| | ICASDE | Cascade correction flag |
| | ALPHA | Local angle of attack (degrees) |
| | THET | Local blade angles (degrees) |
| | TAUB | Chord-to-gap ratio (NDN) |
| | ZM | Local Mach number (NDN) |
| | DECL | Design lift coefficient (NDN) |
| | HØB | Thickness-to-chord ratio (NDN) |
| | ZMCRØM | Critical Mach number (NDN) |
| | CL2 | Lift coefficient (NDN) |
| | CL3 | Temporary lift coefficient (NDN) |
| | CD | Drag coefficient (NDN) |
| | DCDCL | Change in drag coefficient with lift coefficient (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| BIGMAT (Large Storage Matrix, used primarily for wake geometry and matrix coefficient storage) | | |
| | PHI | Wake segment azimuth angles (degrees) |
| | CØSPHI | Cosine of wake azimuth angles |
| | SINPHI | Sine of wake azimuth angles |
| | RW | Radial coordinate of wake segments (NDN) |
| | ZW | Axial coordinate of wake segments (NDN) |
| CASDT (Store Cascade and Airfoil Related Data) | | |
| | SIGMAX | Section cascade solidity, gap-to-chord ratio (NDN) |
| | THETAG | Geometric angle between section chordwise vector and rotation plane (degrees) |
| | THETAB | Section angle of attack neglecting induced terms (degrees) |
| | TAUB | Section chord-to-gap ratio (NDN) |
| CDPER (Store Nacelle Drag Quantities) | | |
| | DFR | Nacelle skin friction drag (lb) |
| | DPR | Nacelle pressure drag (lb) |
| CCØM (Store Section Chord Data) | | |
| | CHØRD | Blade element section chord length (feet) |
| | ALCRAD | Blade element section chord length radial direction cosine (NDN) |
| | ALCPHI | Blade element section chord length tangential direction cosine (NDN) |
| | ALCAXL | Blade element section chord length axial direction cosine (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| CINCØM (Store Input Chord Data) | | |
| | CINPUT | Input chord length (feet) |
| CLCDDT (Store Circulation Solution and Airfoil Characteristics) | | |
| | CLSAV | Section lift coefficient (NDN) |
| | CDSAV | Section drag coefficient (NDN) |
| | ALPHA | Section angle of attack (degrees) |
| | PHINSD | Section inflow angle (degrees) |
| | $CD_o$ | Section minimum drag coefficient (NDN) |
| | CIRC | Section circulation ($ft^2$/sec) |
| | SAVGIR | Section circulation from previous iteration ($ft^2$/sec) |
| | FTRAN | Interpolation function (NDN) |
| CØNSTI (Store Input Data) | | |
| | RPM | Propeller rotational velocity (rmp) |
| | SØUND | Freestream speed of sound (fps) |
| | DENSTY | Freestream density (slugs/$ft^3$) |
| | VIMØM | Momentum induced velocity (fps) |
| | BL | Number of propeller blades per propeller |
| | R | Blade radius (feet) |
| | STN | Number of inflow stations |
| | THETAO | Blade angle (degrees) |
| | HUBQ | Hub torque (ft-$lb_f$) |
| | DPSI | Blade azimuth increment (degrees) |
| | REV | Number of wake revolutions |
| | CPI | Requested power coefficient (NDN) |
| | TØL | Matrix solution tolerance (NDN) |
| | CNSECT | Fraction of blade chord measured from leading edge (NDN) |
| | SCØ | Not used |
| | RADCAS | Blade radius denoting the end of the cascade region (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| | VØRCØR | Vortex core (NDN) |
| | DCPDT | Change in power coefficient with blade angle (per degree) |
| | STACK | Position of lifting line as a fraction of the blade chord measured from the leading edge (NDN) |
| | CTI | Requested thrust coefficient (NDN) |
| | DCTDT | Change in thrust coefficient with blade angle (per degree) |
| | ZHUB | Coaxial hub displacement (NDN) |
| | VKTAS | Freestream velocity (knots) |
| | TIPM | Tip Mach number (NDN) |
| | RDTRAN | Interpolation radius limit (NDN) |
| | RPMREF | Reference rpm for steady load induced twist (rpm) |
| | DPSIB | Blade spacing azimuth interval (degrees) |
| | OMEGA | Propeller rotational speed (rad/sec) |
| | DTIME | Periodic blade/wake geometry time interval (sec) |
| CØNST1 (Store Internal Constants) | | |
| | PI | $\pi$ |
| | RC | $\pi/180$ (radial degree) |
| | R4PI | $4\pi$ x blade radius (feet) |
| | ØNØ4PI | 1/R4PI (per ft.) |
| CØNST2 (Store Miscellaneous Quantities) | | |
| | DIA | Propeller diameter (feet) |
| | ØMGR | Propeller tip speed (fps) |
| | ZMSQ | Freestream Mach number squared (NDN) |
| | UAX | Freestream velocity (fps) |
| | ZJI | Freestream advance ratio (NDN) |
| | MU | Freestream velocity/tip speed (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| CØNST3 (Store Input Option Scalars) | | |
| | PRØPMN | See description for scalar inputs |
| | PRMAT | " |
| | PRØPT | " |
| | DEBUG | " |
| | PCHPLT | " |
| | WAKEØP | " |
| | WAKNAC | " |
| | CØMPRS | " |
| | EVAARD | " |
| | SKINØP | " |
| | CASCAD | " |
| | TYPCAS | " |
| | CBWAKE | " |
| | CØFLØW | " |
| | TAUEXP | " |
| CPTHET (Store Performance Related Quantities) | | |
| | NCP | Performance iteration counter |
| | ICPØK | Performance iteration control flag |
| | THETO | Blade angle storage vector (degrees) |
| | CPCALC | Power coefficient storage vector (NDN) |
| | CTCALC | Thrust coefficient storage vector (NDN) |
| FCØM (Store Force Data) | | |
| | FTØT | Total force per unit area ($lb_f/ft^2$) |
| | ALFRAD | Total force per unit area radial direction cosine (NDN) |
| | ALFPHI | Total force per unit area tangential direction cosine (NDN) |
| | ALFAXL | Total force per unit area axial direction cosine (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| | FLTØT | Lift force per unit area ($lb_f/ft^2$) |
| | ALFLRD | Lift force per unit area radial direction cosine (NDN) |
| | ALFLPH | Lift force per unit area tangential direction cosine (NDN) |
| | ALFAX | Lift force per unit area axial direction cosine (NDN) |
| | FDTØT | Drag force per unit area ($H_{ef}/ft^2$) |
| | ALFDRD | Drag force per unit area radial direction cosine (NDN) |
| | ALFDPH | Drag force per unit area tangential direction cosine (NDN) |
| | ALFDAX | Drag force per unit area axial direction cosine (NDN) |
| FLIGHT (Store Freestream Quantities) | | |
| | ZMO | Local station rotational Mach number (NDN) |
| | ZJO | Local station advance ratio (NDN) |
| FLØWDT (Store Inflow Distribution Data) | | |
| | DENS | Section density ratio (NDN) |
| | SØUN | Section speed of sound ratio (NDN) |
| | VØNVO | Section axial inflow velocity ratio (NDN) |
| | URØNVO | Section radial inflow velocity ratio (NDN) |
| | VZERØ | Section center axial inflow velocity (fps) |
| | VZERØB | Section boundary axial inflow velocity (fps) |
| GCDIMD (Store Geometric Influence Coefficients) | | |
| | GCDIM | Radial, tangential and axial geometric influence coefficients (per ft) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| GCKDAT (Store individual trailing filament and bound vortex influence coefficients) | | |
| | GCKRTZ | Radial, tangential and axial trailing vortex filament influence coefficients |
| | GCRTZB | Radial, tangential and axial bound vortex influence coefficients |
| GEØDAT (Store Blade Geometry Quantities) | | |
| | RSB | Input x-wise segment boundary coordinate (NDN) |
| | ZSB | Input axial segment boundary coordinate (NDN) |
| | YSB | Input y-wise segment boundary coordinate (NDN) |
| | RSBB | Segment boundary radius (NDN) |
| | ZSBB | Segment boundary droop (axial) displacement (NDN) |
| | YSBB | Segment boundary lag displacement (NDN) |
| | PHIBB | Segment boundary lag angle (degrees) |
| | RSC | Input segment center radial coordinate (NDN) |
| | RSCC | Input segment center radial coordinate (NDN) after blade angle rotation |
| | ZSCC | Input segment center axial displacement (NDN) after blade angle rotation |
| | YSCC | Input segment center lag displacement (NDN) after blade angle rotation |
| | PHICC | Input segment center lag angle (degrees) |
| | XSBB | Segment boundary x-wise location (NDN) |
| | XSCC | Segment center x-wise location (NDN) |
| | COSLB | Cosine of blade segment boundary lag angle |
| | SINLB | Sine of blade segment boundary lag angle |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| GEØINP (Store Input Interpolation Arrays) | | |
| | VØNVØX | Axial inflow ratio distribution (NDN) |
| | CX | Input chord distribution (feet) |
| | DTHETX | Input pitch angle distribution (degrees) |
| | TØVERX | Input thickness-to-chord ratio distribution (NDN) |
| | BETAB | Load induced twist increment at blade segment boundary points (degrees) |
| | BETAC | Load induced twist increment at blade segment boundary points (degrees) |
| GEØMØD (Store Design Lift Coefficient) | | |
| | DESCLP | Section design lift coefficient (NDN) |
| GEØØUT (Store Blade Section Properties) | | |
| | DTHETA | Input section pitch angle (degrees) |
| | AFØIL | Section airfoil type (NDN) |
| | DESCL | Input section design lift coefficients (NDN) |
| | TØVERC | Section thickness-to-chord ratio (NDN) |
| | BØD | Section chord-to-diameter ratio (NDN) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| G400DT (Store Quantities from Aeroelastic Response Analysis) | | |
| | NG400 | Option flag |
| | NSEG | Number of blade stations in the response analysis |
| | XYZCG | Segment center coordinates of blade stations used in the response analysis |
| | G400CL | Quadratic coefficients for segment $C_\ell$ from the response analysis |
| | G400CD | Quadratic coefficients for segment $C_D$ from the response analysis |
| IØUNIT (Store Standard Input/Output Unit Numbers) | | |
| | NREAD | Standard input unit |
| | NWRITE | Standard print unit |
| | NPUNCH | Standard punch unit |
| INTDT1 (Store Indexing Limits) | | |
| | ITØT | Number of inflow stations |
| | KTØT | Number of inflow station boundaries |
| | JTØT | Number of blade azimuth stations |
| | NREV | Number of revolutions of wake geometry |
| | NBLØØP | Number of blade loops |
| | LTØT | Number of propeller positions |
| | NPRØP | Number of propellers |
| | MTØT | Number of segment endpoints |
| | MSIZE | LTØT*JTØT*JTØT |
| | NBCALC | Number of blade calculations |
| | IFL | Airfoil type index vector |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| INTDT2 (Store Program Option Flags) | | |
| | NCØMPR | Wake compressibility flag |
| | NEVARD | Evvard Tip Relief flag |
| | IPRMAT | Matrix print flag |
| | IPRØPT | Wake geometry print flag |
| | NCFLØW | Section Mach number test flag |
| | IWAKØP | Wake model flag |
| | NACWAK | Nacelle wake correction flag |
| | IVØRT | Vortex core model flag |
| | ISKIN | Skewed flow skin friction drag addition flag |
| | ICASDE | Analytical cascade correction flag |
| | ICAS | Cascade airfoil flag |
| | IDEBUG | Intermediate print flag |
| | NCBWAK | Compressible bound wake flag |
| | IPCH | Card punch option flag |
| | ITYPCS | Cascade option flag |
| | IBLN | Blade number control flag |
| IUNITD (Store Disc Unit Numbers) | | |
| | IUNIT | Disc unit number storage vector for geometric influence coefficients |
| | MUNIT | Disc unit number for matrix solution coefficients |
| MCØNED (Store Tip Mach Cone Coordinates) | | |
| | XMC | Input tip Mach cone definition coordinate x (NDN) |
| | YMC | Input tip Mach cone definition coordinate y (NDN) |
| | ZMC | Input tip Mach cone definition coordinate z (NDN) |
| | XMCT | Tip Mach cone definition coordinate x (NDN) |
| | YMCT | Tip Mach cone definition coordinate y (NDN) |
| | ZMCT | Tip Mach cone definition coordinate z (NDN) |

| Common Block Name | Variable Names | Description of Variables |
| --- | --- | --- |
| MHCØNE (Store Mach Cone Correction Quantities) | | |
| | NSTAT | Inflow station index where tip Mach cone intersects specified fraction of chord line |
| | XKCØNE | Evaard Tip Relief correction factor (NDN) |
| NØRCØM (Store Section Normal Data) | | |
| | ALNRAD | Blade element section normal radial direction cosine (NDN) |
| | ALNPHI | Blade element section normal tangential direction cosine (NDN) |
| | ALNAXL | Blade element section normal axial direction cosine (NDN) |
| PHICØM (Store Nacelle Induced Wake Azimuthal Distortion Quantities) | | |
| | NPHI | Number of azimuth increments affected by nacelle |
| | DELPHI | Incremental azimuthal distortion (degrees) |
| | COSDPH | Cosine of distortion angle |
| | SINDPH | Sine of distortion angle |
| RØLL (Storage of Wake Rollup Quantities) | | |
| | TRUNCT | Tip filament rollup truncation angle (degrees) |
| | TRUNCI | Inboard filaments truncation angle (degrees) |
| | RØLLUP | Number of filaments for rollup |

| Common Block Name | Variable Names | Description of Variables |
| --- | --- | --- |
| STACØM (Store Section Span Data) | | |
| | STABAR | Blade element section length (NDN) |
| | ALSRAD | Blade element section length radial direction cosine (NDN) |
| | ALSPHI | Blade element section length tangential direction cosine (NDN) |
| | ALSAXL | Blade element section length axial direction cosine (NDN) |
| THICKD (Store Thickness Data) | | |
| | THK | Blade element thickness (NDN) |
| UICØM (Store Induced Velocity) | | |
| | UIR | Radial induced velocity (fps) |
| | UIT | Tangential induced velocity (fps) |
| | UIZ | Axial induced velocity (fps) |
| UUCØM (Store Input Noninduced Velocity Data) | | |
| | UR | Radial noninduced velocity (fps) |
| | UT | Tangential noninduced velocity (fps) |
| | UZ | Axial noninduced velocity (fps) |

| Common Block Name | Variable Names | Description of Variables |
|---|---|---|
| VCØM (Store Noninduced Velocity Data) | | |
| | ALPHAN | Noninduced angle of attack (radians) |
| | VS | Spanwise noninduced velocity direction cosine (NDN) |
| | VC | Chordwise noninduced velocity direction cosine (NDN) |
| | VN | Normalwise noninduced velocity direction cosine (NDN) |
| | VTØT | Total noninduced velocity (fps) |
| | ALVRAD | Radial noninduced velocity direction cosine (NDN) |
| | ALVPHI | Tangential noninduced velocity direction cosine (NDN) |
| | ALVAXL | Axial noninduced velocity direction cosine (NDN) |
| VIDAT (Store Induced Velocity) | | |
| | VIS | Spanwise induced velocity (fps) |
| | VIC | Chordwise induced velocity (fps) |
| | VIN | Normalwise induced velocity (fps) |
| WAKDAT (Store Wake Rollup Data) | | |
| | KTRUCT | Filament station index for rollup |
| | JTRUCT | Wake azimuth position index for tip rollup |
| | JTRUCI | Wake azimuth position index for root rollup |

## Nacelle Program

A detailed description of the nacelle portion of the computer program is given in this section. The subroutines and external functions are described individually in alphabetical order. The labeled common blocks are briefly described along with the FORTRAN variables used in them. Flow charts and figures are provided whenever necessary to understand the objectives and theory for the subroutines or external functions.

List of Subroutines and External Functions

| Name | Object |
|---|---|
| ALTMN | Control I/O and calculation flow |
| AMF | Compute isentropic nozzle flow |
| AMFLØ | Calculate Mach number from area ratio |
| AMU | Compute molecular viscosity |
| BATCH | Main routine |
| BILINE | Calculate neighboring points on output line |
| BLDGEO | Locate blade centerline |
| BLDØUT | Store blade parameters on drum |
| BLKDAT | Load block data |
| BLKRED | Read data records from mass storage device |
| BLPARM | Compute boundary layer parameters |
| BPLUSR | Compute law of wall integration constant |
| CALDRM | Read inviscid or viscous solution from drum |
| CALINV | Calculate inviscid flow field |
| CDS | Calculate Roberts' mesh distortion parameter |
| CKINPT | Check input data for radial equilibrium |
| CØØR | Interpolate coordinates |
| CØØRST | Control flow of coordinate calculation |
| CØØR1 | Compute approximate coordinates |
| CØØR3 | Compute coordinate functions |
| CØØR4 | Compute Schwartz-Christoffel parameters |
| CØØR5 | Interpolate wall curvature at station 5 |
| CPLX1 | Evaluate Schwartz-Christoffel transform |
| DAMU | Find derivati 'e of molecular viscosity |

| Name | Object |
|---|---|
| DRØBRT | Compute derivative of Roberts' transformation |
| DRØUT | Drum I/O routine |
| DRUTPE | Transfer data drum to tape |
| ERPIN | Check normal pressure gradient |
| FAMACH | Calculate Mach number from velocity |
| FAVER2 | Compute mean flow |
| FCØLES | Compute Coles velocity profile |
| FCØRCT | Correct truncation error |
| FCPLX | Evaluate complex functions |
| FETA | Calculate distorted mesh |
| FINTG | Integrate complex functions |
| FLØWIN | Set inlet flow |
| FNØRM | Normalize input variables |
| FØRCE | Compute blade forces |
| FØRCL | Compute local blade force |
| FTHIK | Compute blade thickness |
| GBLADE | Compute blade geometry |
| GDUCT | Compute duct shape |
| GEØMCL | Calculate coordinates of lifting line |
| INITQ | Initialize data file parameters for Q array |
| INTFRE | Initialize freestream conditions |
| LØADRR | Loader formatted input |
| MINVRT | Inverts block matrix |
| MYTIME | Dummy time trap |

| Name | Object |
| --- | --- |
| ØUTPUT | Print title page |
| PERFNA | Compute viscous nacelle drag |
| PERFN2 | Compute inviscid nacelle drag |
| PØIS | Solve Poisson equation |
| PØISCF | Set initial quantities in solution procedure |
| PØISØN | Calculate axisymmetric streamline curvature |
| QINTER | Interpolate curvature |
| READPF | Read P and F files |
| READPG | Read variable for curvature calculation |
| RØBRTS | Compute distorted mesh using Roberts' transformation |
| RØUND | Round corners on straight wall ducts |
| SCURVA | Calculate curvature from potential flow solution |
| SLETE | Find blade control surfaces |
| SMØØTH | Smooth duct wall contour |
| SØLVI | Integrate equations of state |
| SPLIN3 | NASA Spline Fit routine |
| STRESI | Compute initial stress distributions |
| STRT | Find inlet flow locations |
| TPRINT | Call CPU time |
| TURB | Compute turbulent viscosity |
| UBLAS | Calculate velocity ratio according to Blasius solution |
| UCØLES | Compute Coles friction velocity |
| WAKCØR | Compute nacelle wake corrections |

| Name | Object |
|---|---|
| WBLEED | Calculate perforated wall bleed |
| WRITPF | Store updated potential flow solution |
| XH | Calculate wall length on ID wall |
| XT | Calculate wall length on OD wall |

## Description of Subroutines and External Functions

This section describes the subroutines and external functions used in the nacelle portion of the analysis. The source name for the main control routine is called BATCH and has the following two entry points: ALTMN and ØFFLNE. The main program determines the entry point ALTMN or ØFFLNE.

## Subroutine ALTMN

Object Controls I/O and calculation of flow.

Options

IREADR=0 Card formated input
IREADR=1 Loader formated input
All IØPTØ and IDBGØ options

Entry Points

ALTMN Initial loading of first case
ØFFLNE Not used

List of Symbols

| | | |
|---|---|---|
| AMACHE | = $M_1$ | , Average inlet Mach number (dimensionless) |
| BBO | = $B_o$ | , Inlet blockage (dimensionless) |
| DZ | = $\Delta Z$ | , Increment in axial length (ft) |
| IREADR | = | , Loader format flag |
| KDSH | = KDS | , Temporary storage for KDS |
| P1 | = $P_1$ | , Average inlet static pressure (psf) |
| REYH | = $N_{Rh}$ | , Reynolds number based on duct height (dimensionless) |
| T1 | = $T_1$ | , Average inlet static temperature (deg R) |
| Z | = Z | , Axial length (ft) |

Theory

This subroutine controls I/O and the calculation of flow depending on the options selected. A flow chart is shown in figure 16.

Subroutine AMF(AA,AM1,AMG,AM,ACPC,ACPI)

Object Compute isentropic nozzle flow

Options

AMG < 1 Subsonic solution
AMG > 1 Supersonic solution

List of Symbols

| | | |
|---|---|---|
| AA | $= A/A_1$ | , Area ratio |
| AAI | $= (A/A_1)^{\nabla}$ | , $\nabla^{th}$ guess for area ratio |
| ACPC | $= C_p$ | , Pressure coefficient |
| ACPI | $= C_{pI}$ | , Incompressible pressure coefficient |
| AM | $= M$ | , Mach number |
| AMF | $= F(M)$ | , Function name |
| AMG | $= M^{(G)}$ | , 1st guess for Mach number |
| AMI | $= M_2^{\nabla}$ | , $\nabla^{th}$ guess for Mach number |
| AM1 | $= M_1$ | , Mach number at station 1 |
| AP2 | $= P_o/P_1$ | , Static pressure at station 1 |
| AP2 | $= P_o/P_2$ | , Static pressure at station 2 |
| C1 | $= \gamma-1/2$ | Constants in Iteration |
| C2 | $= \frac{1}{2}\ \frac{\gamma+1}{\gamma-1}$ | Constants in Iteration |
| C3 | $= M_1/(1+\frac{\gamma-1}{2}\ M_1{}^2)^{\left(\frac{1}{2}\ \frac{\gamma+1}{\gamma-1}\right)}$ | Constants in Iteration |
| C4 | $= (\gamma+1)$ | Constants in Iteration |
| C5 | $= 1+\frac{\gamma-1}{2}(M^{(i)})^2$ | Constants in Iteration |

C6 $= \gamma/\gamma-1 \quad \left(\frac{1}{2}\,\frac{\gamma+1}{\gamma-1}\right)$

C7 $= M_1 \dfrac{(1 + \frac{\gamma-1}{2}\quad)}{(1 + \frac{\gamma-1}{2} M_1^2)} \left(\frac{1}{2}\,\frac{\gamma+1}{\gamma-1}\right)$

$\Big\}$ Constants in Iteration

DAAI $= (dA/dM)^{\nabla}$ , Derivative

DAMI $= \Delta M$ , Correction to Mach number

ITER $= \nabla$ , Iteration counter

Theory

Fiven the area ratio $A/A_1$ and the inlet Mach number $M_1$, find the exit Mach number M, the pressure coefficient $C_p$, and the incompressible coefficient $C_{PI}$. The exit Mach number M is determined from the one-dimensional isentropic flow relations using Newton's method for determining roots of nonlinear equations. Thus, we setup the iteration cycle

$$(A/A_1)^\nu = \frac{C^3}{M^\nu}\left(1 + \frac{\gamma-1}{2}(M^\nu)^2\right)^{\frac{1}{2}\frac{\gamma+1}{\gamma-1}} \tag{1}$$

$$\left[\frac{d(A/A_1)}{dM}\right]^\nu = \left(\frac{A}{A_1}\right)^\nu \left\{\frac{C_4 M^\nu}{C_5} - \frac{1}{M^\nu}\right\} \tag{2}$$

$$\Delta M = (A/A_1 - (A/A_1)^\nu) / \frac{d}{dM}(A/A_1) \tag{3}$$

$$M^{\nu+1} = M^\nu + \Delta M \tag{4}$$

When $|\Delta M| < 10^{-5}$ the iteration has converged and the pressure coefficient may be computed.

$$\frac{P_0}{P_1} = \left(1 + \frac{\gamma-1}{2} M_1^2\right)^{\frac{\gamma}{\gamma-1}} \tag{5}$$

$$C_{PI} = 1 - \left(\frac{A_1}{A}\right)^2 \tag{6}$$

$$C_P = \frac{(P/P_0 - P_1/P_0)}{1 - P_1/P_0} \tag{7}$$

Subroutine AMFLØ (AA, AM1, AMG, AM, ACPC, ACPI)

Object Calculate Mach number from area ratio

Variables

| | | |
|---|---|---|
| AA | A/A | Area ratio |
| ACPC | $C_{PC}$ | Compressible pressure coefficient |
| ACPI | $C_{PI}$ | Incompressible pressure coefficient |
| AM | M | Mach number |
| AMG | | Flag |
| AM1 | $M_1$ | Mach number at station 1 |

Theory

The Mach number can be calculated from

$$\frac{A}{A_1} = \frac{M_1}{M}\left(\frac{1 + \frac{\gamma-1}{2} M^2}{1 + \frac{\gamma-1}{2} M_1{}^2}\right)^{\frac{\gamma + 1}{2(\gamma-1)}} \tag{1}$$

using Newton's iteration. With M known,

$$C_{PI} = 1 - \left(\frac{A_1}{A}\right)^2 \tag{2}$$

$$\frac{P_T}{P_1} = [1 + \frac{\gamma-1}{2} M_1{}^2]^{\frac{\gamma}{\gamma-1}} \tag{3}$$

$$\frac{P_T}{P} = [1 + \frac{\gamma-1}{2} M^2]^{\frac{\gamma}{\gamma-1}} \tag{4}$$

$$C_{PC} = \left(\frac{P}{P_T} - \frac{P_1}{P_T}\right) / \left(1 - \frac{P_1}{P_T}\right) \tag{5}$$

AMG < Subsonic root of (1)

AMG > Supersonic root of (1)

## Function AMU(T)

Object  Compute molecular viscosity

Options

None

List of Symbols

| | | |
|---|---|---|
| AMU | $= \mu/\mu_r$ | , Ratio of molecular viscosity (dimensionless) |
| T | $= \Theta$ | , Static temperature ratio (dimensionless) |

Theory

The molecular viscosity is computed according to Sutherland's formula (Ref. 6). The working fluid is assumed to be air. Accordingly,

$$\frac{\mu}{\mu_r} = \Theta^{3/2} \frac{1 + 198.0/T_r}{\Theta + 198.0/T_r} \tag{1}$$

## Subroutine BLDØUT

Object  Write (or read) blade parameters on drum

Entry Points  BLDIN
BLDØUT
BLDIND
BLDØUD
BLDBK

List of Symbols

| | |
|---|---|
| STRI, STR3, STR5, STR7, ISTR8 | blade parameters (dimensional) |
| STR2, STR4, STR6 | blade parameters (nondimensional) |

Theory

Blade parameters for each row of blades are stored on a drum. This routine will read or write onto that drum.

## Main Program BATCH

Object    Main program

Variables  None

Theory

The main programs calls only subroutines TITLE and ALTMN

## Subroutine BILINE (L,RB1,ZB1,RB2,ZB2)

### Object

Calculate neighboring points on output line

### Options

None

### Variables

L , Point number

RB1,ZB1 = $\bar{R}_1,\bar{Z}_1$ , Point at L-1

RB2,ZB2 = $\bar{R}_2,\bar{Z}_2$ , Point at L

### Theory

The points are read from an input table.

## Subroutine BLDGEØ

### Object

Locate blade centerline in (n,s) coordinates

### Options

| | | |
|---|---|---|
| IØPT2 | = 0 | No blades in duct |
| | = 1 | Blades in duct |

### List of Symbols

CØMMON BLØCK Variables

### Theory

This subroutine uses subroutine FLINE to find the centerline in the (n,s) coordinates. Thus the input data from the blade stacking plane is transformed to the duct plane using subroutine TRBLD and stored in the input data line data block BLNE (I,2) used by subroutine FLINE. The output (n,s) coordinates are then stored in the blade data array CONST(I,L). At the completion of this calculation, the location of the upstream and downstream blade force calculation surfaces are determined by calling subroutine SLETE.

## Subroutine BLKDAT

<u>Object</u> Load fixed constants to program.

<u>Options</u>

None

<u>List of Symbols</u>

| | | |
|---|---|---|
| ACHI | $= \chi$ | , 0.016 (dimensionless) |
| AKAPPA | $= K$ | , 0.41 (dimensionless) |
| APLUS | $= A^+$ | , 26.0 (dimensionless) |
| CPR | $= C_{pr}$ | , 5997. ($ft^2/sec^2$/deg R) |
| CVR | $= C_{vr}$ | , 4283.($ft^2/sec^2$/deg R) |
| EP | $= e$ | , 2.7182818 (dimensionless) |
| GAMMA | $= \gamma$ | , 1.4 (dimensionless) |
| GASR | $= \mathcal{R}$ | , 1714. ($ft^2/sec^2$/deg R) |
| GRAVR | $= g$ | , 32.2 (ft/$sec^2$) |
| PI | $= \pi$ | , 3.1415926 |
| PRESR | $= P_r$ | , 2117. ($ft^2/sec^2$/deg R) |
| PRL | $= P_{rL}$ | , 0.72 (dimensionless) |
| PRT | $= P_{r_t}$ | , 0.90 (dimensionless) |
| RHØR | $= \rho_r$ | , 0.00238 (slugs/$ft^3$) |
| SNDR | $= C_r$ | , 1116.0 (ft/sec) |
| TEMPR | $= T_r$ | , 519.0 (deg R) |
| TI | $= t$ | , 0.01745329 (dimensionless) |
| VISCR | $= \mu_r$ | , $0.37 \times 10^{-6}$ (slug/ft/sec) |

Values of parameter's defined in CØMMØN/PARAM/ are also included for IBM and CDC computer programs.

Subroutine BLKRED (UNIT, RECSIZ, ADDR, BEGREC, NRECS)

Object

Reads NREC 'records' from file 'UNIT' beginning with record BEGREC. NRECS records are stored as a single block, beginning at ADDR. The Univac 1100 library I/O routine NTRAN is used in this subroutine.

Variables

| | | | |
|---|---|---|---|
| UNIT | = | logical unit# | (Integer) |
| RECSIZ | = | record size in words | (Integer) |
| BEGREC | = | first record to read | (Integer) |
| NRECS | = | # of logical records to read | (Integer) |
| ADDR | = | beginning address to store the NRECS & RECSIZ records read | |

Theory

BLKRED (with entry BLKWRT) was developed to allow NTRAN compatibility with ANSI standard DEFINE FILE I/O operations. In particular, a call to BLKRED with NRECS = 1 is identical to a random access fortran read.

In order to simulate DEFINE FILE I/O, it is necessary for BLKRED to maintain a list of pointers into the various disk files. The pointer list, DSKLOC, is in a common block |UNITS| which must be allocated in a static (root) segment. The location pointer and read size are used to position the disk for I/O access. After the I/O access, the pointer is positioned accordingly.

BLKRED will issue a diagnostic message and cause program termination if either of two abnormal conditions are detected.

1) the record # is negative

2) NTRAN returns on error status less than zero (see UNIVAC FORTRAN V library routine NTRAN description on UNIVAC ASCII FORTRAN routine NTRAN$ description)

## Subroutine BLPARM

**Object** Calculate boundary layer parameters from viscous solution.

**Options** II = 1 Calculate hub boundary layer
II = 2 Calculate tip boundary layer

**List of Symbols**

| | | |
|---|---|---|
| BLC(1, I) | $= U_\infty$ | Freestream velocity |
| BLD(2, I) | $= \Pi$ | Static pressure |
| BLP(3, I) | $= T_o$ | Total temperature |
| BLP(4, I) | $= T$ | Static temperature |
| BLP(5, I) | $= M$ | Mach number |
| BLP(6, I) | $= U_s$ | Streamwise velocity |
| BLP(7, I) | $= \rho$ | Density |
| BLP(8, I) | $= Y$ | Distance from hub |
| BLP(9, I) | $= \Delta^*/\Delta_1$ | Displacement thickness ratio |
| BLP(10, I) | $= \theta^*/\theta_1$ | Momentum thickness ratio |
| BLP(11, I) | $= \Delta^*/\theta^*$ | Shape factor |
| BLP(12, I) | $= N_\theta$ | Reynolds number |
| CF | $= C_f$ | Wall Friction Coefficient |

**Theory**

This subroutines determines the momentum thickness $\theta^*$ and the displacement thickness $\Delta^*$ where

$$\Delta^* = \int_0^\infty \frac{\rho}{\rho_\infty}\left(1 - \frac{U}{U_\infty}\right) dy$$

$$\theta^* = \int_0^\infty \frac{\rho}{\rho_\infty}\left(\frac{U}{U_\infty} - \frac{U^2}{U_\infty^2}\right) dy$$

## Function BPLUSR (AKPLUS)

Object Compute the law of wall integration constant for initial profile.

Options None

None

List of Symbols

| | | |
|---|---|---|
| AKPLUS | $K_S^+$ | , Roughness Reynolds number |
| BPLUSR | $B^+(K_S^+)$ | , Integration constant |

Theory

The inner layer turbulence model given in FCOLES was integrated to get the constant of integration. A data correlation for $B^+(K_S^+)$ is then given by

$$B^+(0) = 2.2 \quad , \quad K_s^+ < 4.1270 \tag{1}$$

$$B^+(K_s^+) = -0.81486 - 1.2070 \cdot (\ln K_s - 3.91538) \quad , \quad K_s^+ > 4.1270 \tag{2}$$

Equation (1) indicates that for $K_S^+ < 4.127$, the smooth wall model applies.

## Subroutine CALDRM

Object Read inviscid or viscous solution from (drum)

Options

NØPT8 = 0 Read inviscid solution
NØPT8 = 1 Read viscous solution

List of Symbols

| | |
|---|---|
| F | Viscous flow parameters |
| CINP | Inviscid flow parameters |

## Subroutine CALINV

Object  Calculate inviscid flow field solution.

Options

Calculate flow from J = JFIRS, JLAS
  IF (IØPT15.NE.0) JFIRS=IØPT15
  IF (IØPT16.NE.0) JLAS=IØPT16
Calculate only for IØPT1 = 3 or 4
  NOPT5 $\neq$ 0 Error exit

List of Symbols

Same as CKINPT

Variable store on drum  K=1,KL

| | | |
|---|---|---|
| BINP(1, K) | $P_o$ | , Total pressure (psf) |
| BINP(2, K) | P | , Static pressure (psf) |
| BINP(3, K) | $\alpha$ | , Swirl angle (deg) |
| BINP(4, K) | $T_o$ | , Total temperature (deg R) |

Additional Variables

| | | |
|---|---|---|
| ITERAL | $V_\alpha$ | , Swirl angle iteration number |
| ERRA | $E_\alpha$ | , Local error in swirl angle |
| ERRAM | $E_{nd}$ | , Maximum error in swirl angle |

Theory

Given the swirl angle $\alpha$, the analysis is identical to subroutine CKINPT. The calculation of the inviscid flow field requires also the solution of the angular momentum equation which is given by

$$RU_\phi = R_i U_{\phi_i} \tag{1}$$

where $RU_\phi$ is the angular momentum at an arbitrary station and $R_i U_{\phi i}$ is the inlet angular momentum which is given. An outer iteration loop is then programmed to solve eqt. (1) to get the swirl angle $\alpha$. With $\alpha$ known, the inner iteration loop is the same as subroutine CKINPT. This solution is obtained for each streamwise station J = JFIRS, JLAS. The computed solution BINP (4, KL) is stored on a drum.

Function CDS (DDS, DETA)

Object

Calculate Roberts' mesh distortion parameter

Options

None

Input Variables

DDS = Ratio of mesh distortion at wall $\Delta\eta/\Delta n$

DETA = $\Delta\eta$ , Mesh size at boundary - uniform mesh
$\Delta n$ , Distorted mesh size at wall

Output Variables

CDS $c$ , Roberts' mesh parameter

Theory

Let $$c = 1/2 + \epsilon \tag{1}$$

Then Roberts' transformation can be written

$$\phi = \left(\frac{1+\epsilon}{\epsilon}\right)^{(2\Delta\eta-1)} \tag{2}$$

$$\Delta n = \frac{(1+\epsilon)\phi - \epsilon}{1+\phi} \tag{3}$$

$$\Delta n = \Delta\eta/\mathrm{DDS} \tag{4}$$

Eq. (2) through (4) can be solved iteratively for $\varepsilon$ as follows:

$$\epsilon = 0 \tag{5}$$

$$\phi = \frac{\Delta n + \epsilon}{1+\epsilon-\Delta n} \tag{6}$$

$$\epsilon = \left[\phi^{\frac{1}{2\Delta\eta-1}} - 1\right]^{-1} \tag{7}$$

Convergence occurs when

$$\left| \frac{\epsilon^{\nu+1} - \epsilon^{\nu}}{\epsilon^{\nu}} \right| < 1E-04 \tag{8}$$

## Subroutine CKINPT

Object    Check input data for radial equilibrium

Options

| | |
|---|---|
| IØPT1 ≠ 4 | Do not calculate |
| NØPT5 ≠ 0 | Error exit |
| IØPT5 = 2 | FØRCE data equals FLØWIN data |
| IJ = 1 | Inlet flow data |
| IB = 2 | Force data |
| INEX = 1 | Upstream data |
| INEX = 2 | Downstream data |
| IDBG13 = 1 | Debug printout |
| WFLØW = 0 | Static pressure check only |
| WFLØW > 0 | Pressure check and weight flow iteration |

List of Symbols

| | | |
|---|---|---|
| ERR | $\varepsilon$ | , Error in interaction |
| EPS | $\varepsilon_o$ | , Minimum error |
| FG(2, K) | $\phi(2)$ | , Equation 4 |
| FG(4, K) | $\Phi(2)$ | , Equation 5 |
| ITER | V | , Iteration number |
| PHMAX | | , Maximum pressure possible |
| PSI1, PSI2 | $\psi_1^v$, $\psi_2^v$ | , Upper and lower bound air stream function |
| WF | $W^{v2}$ | , Weight flow $v^{th}$ iteration |
| WFLØW | W | , Input weight flow |
| WMAX | $W_{max}$ | , Maximum weight flow possible |

| | | | |
|---|---|---|---|
| WMIN | $W_{min}$ | , | Minimum weight flow possible |
| XL | $X_L$ | , | Lower bound on X |
| XM | $X_M$ | , | X for choked flow |
| XU | $X_U$ | , | Upper bound on X |
| X1 | $X_1^u$, $X_2^u$ | , | Iterative values for X |
| PSIHT,PSIT | $\psi_T$, $\psi_T^u$ | , | Value of stream function |

Theory

Input data for the total pressure, static pressure, swirl angle, and total temperature must satisfy the continuity equation, and the radial momentum equation. If these equations are not satisfied, the static pressure is adjusted. The solution of these equations can be obtained by a transformation of variables. Let

$$X = \left(\frac{\Pi}{\Pi_0}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

and

$$a(\eta) = 2\left\{-\frac{1}{XV}\frac{\partial V}{\partial n}\cos^2\alpha + \frac{1}{XR}\frac{\partial R}{\partial n}\sin^2\alpha\right\} \tag{2}$$

then the radial momentum equation becomes

$$\frac{dX}{dt} + \left[a(\eta) + \frac{\gamma-1}{\gamma}\frac{d}{d\eta}(\ln\Pi_0)\right]X = a(\eta) \tag{3}$$

which is an ordinary first order "linear" equation. The solution is given by

$$\phi(\eta) = \exp\left\{\int_0^\eta a(\gamma)\,d\gamma + \frac{\gamma-1}{\gamma}\ln\left(\frac{\Pi_0}{\Pi_{0H}}\right)\right\} \tag{4}$$

$$\Phi(\eta) = \int_0^\eta a(\gamma)\,\phi(\gamma)\,d\gamma \tag{5}$$

$$X = (X_0 + \Phi(\eta))/\phi(\eta) \tag{6}$$

where $X_o$ is the hub static pressure ratio. The continuity equation becomes

$$\frac{d\Psi}{d\eta} = \frac{\Pi_0 G \cos\alpha}{M_r V \sqrt{\Theta_0}} X^{\frac{1}{\gamma-1}} (1-X)^{1/2} \tag{7}$$

and

$$w(\eta) = 2\pi \rho_r c_r r_r^2 g \Psi(\eta) \tag{8}$$

The constant $X_o$ is determined by the boundary condition

$$w(1) = w \tag{9}$$

using an iteration scheme described below.

First let us examine the function

$$f(X) = X^{\frac{1}{\gamma-1}} (1-X)^{1/2} \tag{10}$$

f(X) has a maximum at

$$X = X_m = \frac{2}{\gamma+1} \tag{11}$$

Hence from equation (1)

$$\frac{\Pi_M}{\Pi_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{12}$$

Equation (12) is precisely the condition for choked flow when $M = 1$. Substitution of equation (12) into equation (10) yields an a priori condition for the maximum weight flow possible (i.e., the choked flow condition). For a subsonic solution we then have the condition

$$\frac{2}{\gamma+1} < X < 1 \tag{13}$$

Furthermore, it is noted that we can find a priori $X_o$ such that

$$\begin{aligned} &\frac{2}{\gamma+1} < X_L < X_0 < X_\mu < 1 \\ &f(X_L) < f(X_M) \\ &f(X_0) > 0 \end{aligned} \tag{14}$$

by substituting equation (6) into equation (10). Thus $X_L$ and $X_U$ are the bounds for choosing subsonic solutions with no reverse flow. The iteration scheme then consists of narrowing the bounds of $X_L$ and $X_U$ until convergence occurs. This procedure is illustrated in figure 17.

$$X^{V+1} = X_1^V + \frac{\Psi - \Psi_1^V}{\Psi_2^V - \Psi_1^V}\left(X_2^V - X_1^V\right) \tag{15}$$

$$\begin{aligned} &\text{If}\left(\Psi^{V+1} < \Psi\right)\ X_1^V = X^V\ ;\ \Psi_1^V = \Psi \\ &\text{If}\left(\Psi^{V+1} > \Psi\right)\ X_2^V = X^V\ ;\ \Psi_2^V = \Psi \end{aligned} \tag{16}$$

and $\psi^V$ is obtained by integrating equation (7) with $X_o = X^{V+1}$ substituted into equation (6). Convergence occurs when

$$\left|X^{V+1} - X^V\right| < \xi_0 \tag{17}$$

Once X is known, the static pressure is obtained from (1) and substituted for the input static pressure.

## Subroutine CØØR(JS,KS)

Object  Controls logic in determining coordinates and interpolates coordinates streamwise.

Options

IØPT9=0  Computes approximate coordinates
IØPT9≠0  Coordinates stored on drum
IØPT9=1  Compute exact coordinate functions and store on drum
IØPT9=3  Read coordinates from drum

List of Symbols

| | | | |
|---|---|---|---|
| DSTEP | = | $\Delta S$ | , Streamwise step size (dimensionless) |
| DX | = | $\Delta X$ | , Interpolation between JS and JS-1 stations |
| DXNEXT | = | $\Delta X_N$ | , Interpolation for next step |
| JDRUM | = | | , Drum unit number |
| JS | = | | , $JS^{th}$ station stored on drum |
| KS | = | | , $KS^{th}$ station interpolated between JS |
| ZHUB | = | $Z_H$ | , Axial station hub (dimensionless) |
| ZNEXT | = | $Z_N$ | , Next axial station (dimensionless) |
| ZTIP | = | $Z_T$ | , Axial station Tip (dimensionless) |

Theory

Let the streamwise coordinate S be given by

$$S = \Delta S(JS-1) + dS \cdot (KS-1) \quad (1)$$

where

$$\Delta S = S_L/(JLAST-1) \quad (2)$$

$$dS = \Delta S/KDS \quad (3)$$

Then if station 1 is at JS-1 and station 2 at JS, a simple linear interpolation of the coordinates may be made from those stored on the drum. ZNEXT is the axial location of the KS+1 station.

Subroutine CØØP5 (XH, XT, CURVH, CURVT)

Object

Interpolate wall curvature at Station S

Options

None

Variables

| | | | |
|---|---|---|---|
| XH | $X_H(S)$ | , | Arc length ID wall (dimensionless) |
| XT | $X_T(S)$ | , | Arc length OD wall (dimensionless) |
| CURVH | $K_H(S)$ | , | Curvature ID wall (dimensionless) |
| CURVT | $K_T(S)$ | , | Curvature OD wall (dimensionless) |
| RM(3,J) | $X_{HI}(J)$ | , | Table of $X_H$ (dimensionless) |
| RM(4,J) | $K_{HI}(J)$ | , | Table of $K_H$ (dimensionless) |
| RM(7,J) | $X_{TI}(J)$ | , | Table of $X_T$ (dimensionless) |
| RM(8,J) | $K_{TI}(J)$ | , | Table of $K_T$ (dimensionless) |

Theory

The values of $X_H(S)$ and $X_T(S)$ are input. Then the tables are searched and the values of $K_H(S)$, $K_T(S)$ are calculated by linear interpolation.

## Subroutine CØØRST

Ojbect  Controls flow of coordinate calculation

Options  None

List of Symbols

| | | |
|---|---|---|
| DSTEP | $= \Delta S =$ DS | , Streamwise step size (dimensionless) |
| DX | $= \Delta\eta$ | , Normal coordinate step size (dimensionless) |
| DY1 | $= \delta Y$ | , First derivative (dimensionless) |
| DY2 | $= \delta^2 Y$ | , Second derivative (dimensionless) |
| ICK | = 0,1 | , Flag; no overlap, overlap |
| II | = 1,2 | , Flag; start integration, continue integration |
| ISLT1, ISLT2 | = | , First slot number, second slot number |
| IW1,IW2 | = | , First slot wall, second slot wall |
| JCØUNT | = | , Streamwise station counter |
| KLHØLD | = | , Number of streamlines to interpolate |
| KN | = | , Number of streamlines to integrate |
| MSLØT | = | , Slot counter |
| NSLØT | = | , Total number of slots |
| RA(I,J) | = R(I,1,J) | , Temporary storage for wall coordinate |
| X | = X | , Normal coordinate (dimensionless) |

| | | |
|---|---|---|
| XM | = $X$ | , Interpolation distance (dimensionless) |
| X2 | = $X_2$ | , Midpoint of three point difference (dimensionless) |
| Y | = $Y$ | , Function to be interpolated (dimensionless) |
| Y1 | = $Y(X_r)=Y_1$ | , Known values of Y (dimensionless) |
| Y2 | = $Y(X_2)=Y_2$ | , Known values of Y (dimensionless) |
| Y3 | = $Y(X_3)=Y_3$ | , Known values of Y (dimensionless) |
| Z | = $Z$ | , Axial distance (dimensionless) |
| $ZZ_1, ZZ_2$ | = $Z_1$, $Z_2$ | , Location of adjacent slots (dimensionless) |

Theory

This subroutine controls the calculation flow for the coordinates according to flow chart figure 18. The basic calculation scheme with slots is to calculate the streamlines through successively larger ducts and storing only those coordinates satisfying the condition ($Z_1 \leq Z \geq Z_2$) as shown in figure 19.

In addition, it was determined that only KN streamlines need be calculated by integration, the remainder up to KL streamlines may be calculated using a parabolic interpolation.

Subroutine CØØR1 (KSS,JSS)

Object  Compute approximate coordinate functions.

Theory

This subroutine provides an initial guess from the iterative method described in reference 6 which is used to approximate the coordinate functions and hence determine the numerical grid structure used in the flow analysis.

Subroutine CØØR3(KSS,JSS,LØP)

Object  Compute coordinate functions (IØPT9=1,2).

Options

LØP=1  Compute initial constants
LØP=2  Integrate one step
LØP=3  Do not integrate

List of Symbols

| | | | |
|---|---|---|---|
| AO | = | $A_o$ | , Inlet height W plane (dimensionless) |
| ALO | = | $\alpha o$ | , Inlet angle W plane (dimensionless) |
| ANO | = | $n_o$ | , Inlet height Z plane (dimensionless) |
| SLO | = | $S_L{}^o$ | , Initial coordinate length (dimensionless) |
| RO | = | $r_o$ | , Inlet radius Z plane (dimensionless) |
| VO | = | $v_o$ | , Inlet metric scale coefficient (dimensionless) |
| SO | = | $s_o$ | , Inlet streamwise coordinate (dimensionless) |
| XBO | = | $\tilde{X}_o$ | , Real part of $C_1$ (dimensionless) |
| YBO | = | $\tilde{Y}_o$ | , Imaginary part of $C_1$ (dimensionless) |
| ZETAO | = | $\xi_o$ | , Constant of integration (real) (dimensionless) |
| ETAO | = | $\eta_o$ | , Constant of integration (imaginary) (dimensionless) |

Theory

Using procedures described in reference (6), one can integrate along streamlines to get R, Z, V, S, N at the location of the poles $b_I$.

## Subroutine CØØR4

<u>Object</u> Find Schwartz-Christoffel parameters.

<u>Options</u>

None

<u>List of Symbols</u>

| | | | |
|---|---|---|---|
| AX(1,J) | = | $X_H$ | , Distance along hub wall (dimensionless) |
| AX(2,J) | = | $X_T$ | , Distance along tip wall (dimensionless) |
| AX(3,J) | = | $\alpha_H$ | , Wall angle hub (deg) |
| AX(4,J) | = | $\alpha_T$ | , Wall angle tip (deg) |
| AY(1,I,J) | = | $S_H^\nu$ | , Streamwise coordinate hub (dimensionless) |
| AY(2,I,J) | = | $X_H^\nu$ | , Distance along hub wall (dimensionless) |
| AY(3,I,J) | = | $V_H^\nu$ | , Metric scale coefficient hub (dimensionless) |
| AY(4,I,J) | = | $R_H^\nu$ | , Radius hub (dimensionless) |
| AY(5,I,J) | = | $S_T^\nu$ | , Streamwise coordinate tip (dimensionless) |
| AY(6,I,J) | = | $X_T^\nu$ | , Distance along tip wall (dimensionless) |
| AY(7,I,J) | = | $V_T^\nu$ | , Metric scale coefficient tip (dimensionless) |
| AY(8,I,J) | = | $R_T^\nu$ | , Radius tip (dimensionless) |
| AERR(1,J) | = | $S_H^{\nu+1} - S_H^\nu$ | , Error in $S_H$ (dimensionless) |
| AERR(2,J) | = | $S_T^{\nu+1} - S_T^\nu$ | , Error in $S_T$ (dimensionless) |
| AO | = | $h_o$ | , Inlet height W plane (dimensionless) |
| ALO | = | $\alpha_o$ | , Inlet angle W plane (dimensionless) |
| ANO | = | $n_o$ | , Inlet height Z plane (dimensionless) |
| SLO | = | $S_L^o$ | , Initial guess of coordinate length (dimensionless) |

RO = $r_o$ , Inlet radius in Z plane (dimensionless)

VO = $V_o$ , Inlet metric scale coefficient (dimensionless)

SO = $S_o$ , Inlet streamwise coordinate (dimensionless)

XBO = $\tilde{X}_o$ , Real part of constant $C_1$ (dimensionless)

YBO = $\tilde{Y}_o$ , Imaginary part of constant $C_1$ (dimensionless)

ZETAO = $\xi_o$ , Constant of integration (real) (dimensionless)

ETAO = $\eta_o$ , Constant of integration (imaginary) (dimensionless)

Theory

The theory to this subroutine is described in reference (1).

Subroutine CPLX1(X1,Y1,XB1,YB1,N1,N2,LØP)

Ojbect  Evaluates Schwatz-Christoffel transform.

Options

LOP=1 $W_Z = \tilde{X} + i\tilde{Y} = dW/dZ$

=2 $W_{ZZ} = \tilde{X} + i\tilde{Y} = d^2W/dZ^2$

List of Symbols

| | | | |
|---|---|---|---|
| N1 | = | $N_1$ | , Product index |
| N2 | = | $N_2$ | , Product index |
| N3 | = | $N_1+1$ | , Product index |
| X1 | = | X | , X coordinate in Z plane |
| Y1 | = | Y | , Y coordinate in Z plane |
| XB1 | = | $\tilde{X}$ | , X coordinate in $W_Z$ plane or $W_{ZZ}$ plane |
| XB2 | = | $\tilde{Y}$ | , Y coordinate in $W_Z$ plane or $W_{ZZ}$ plane |

Theory

This subroutine evaluates the real and imaginary parts of the Schwartz-Christoffel transform.

Function DAMU

Object - Find derivative of molecular viscosity with respect to temperature

List of Symbols

| | |
|---|---|
| T | Temperature |
| D | Derivative |

Theory

The derivative of the molecular viscosity may be expressed as a function of temperature.

$$D = A2 * \left(1.5/T - 1/(T + A1)\right) \qquad (1)$$

where

$$A1 = 198./T \qquad (2)$$

$$A2 = T{*}{*}1.5 * (1+A1) \,/\, (T+A1) \qquad (3)$$

Function DRØBRT (C, ETA, LØP)

Object

Compute derivative of Roberts' transformation

Options

LØP = 0 wall - wall boundary
LØP = 1 wall-freestream boundary
LØP = -1 freestream-wall boundary

Input Variables

| | | |
|---|---|---|
| C = C | , | Distortion parameter |
| ETA = η | , | Input variable |
| LØP | , | Option |

Output Variable

| | | |
|---|---|---|
| DROBRT = ∂η/∂n | , | Output variable |

Theory

The transform of the Roberts' Stretching for a distorted mesh is given by

$$\frac{\partial \eta}{\partial n} = \left[4 \; c \; \ln\left(\frac{c+1/2}{c-1/2}\right) \frac{\phi}{(1+\phi)^2}\right]^{-1} \tag{1}$$

$$\phi = \exp\left[2 \; \ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta' - 1/2\right)\right] \tag{2}$$

where the options are

$$\left.\begin{matrix} \eta' = \eta \\ n = n' \end{matrix}\right\} L\phi P = 0 \qquad \left.\begin{matrix} \eta' = \eta/2 \\ n = 2n' \end{matrix}\right\} L\phi P = 1 \qquad \left.\begin{matrix} \eta' = (1+\eta)/2 \\ n = 2n' - 1 \end{matrix}\right\} L\phi P = -1$$

We note that

$$0 \le \eta' \le 1.0 \qquad 0 \le n' \le 1.0 \tag{3}$$

Subroutine DRØUT (UNIT,ADDR,BLØCK)

<u>Object</u> Tape/Drum Read/Write data

<u>Options - Entry Points</u>

DRØUT(UNIT,ADDR,BLØCK)

Write on drum unit UNIT data contained in ADDR containing BLØCK number of words.

DRMIN(UNIT,ADDR,BLØCK)

Read from drum unit UNIT data contained in ADDR containing BLØCK number of words.

DREWND(UNIT)

Rewind drum unit UNIT.

DRMBK1(UNIT,ADDR, BLØCK)

Back space drum one BLØCK and read as in DRMIN.

DRMBK2(UNIT,ADDR,BLØCK)

Back space drum two BLØCK and read as in DRMIN.

DRMEØUF(UNIT)

Write end of file on unit UNIT (tape only).

TPFILE(UNIT,LFILE)

Find file number LFILE on tape unit UNIT.

<u>Theory</u>

This subroutine is an I/O routine to facilitate conversion of UNIVAC NTRAN I/O routines to other computer systems.

Subroutine DRUTPE(LFILE,JBLØCK,LØPT)

Object  Transfers data Drum/Tape or Tape/Drum.

Options

LØPT=1  Transfer data tape to drum
LØPT=2  Transfer data drum to tape

List of Symbols

| | | |
|---|---|---|
| JBLØCK | = | , Number of records to copy |
| JDRUM | = | , Drum unit number |
| JTAPE | = | , Tape unit number |
| LFILE | = | , Tape file number |

Theory

This subroutine transfers data using subroutine DRØUT.

Subroutine ERPIN(II)

Object  Checks normal pressure gradient for viscous flow

Options

II=1  Check inlet station
II=2  Check J-1 station
II=3  Check J station

List of Symbols

| | | |
|---|---|---|
| ERPIN | $= \mathcal{E}$ | , Error in normal pressure gradient |

Theory

At any station in the duct, the normal momentum equation must be satisfied. This subroutine checks the error.

$$\varepsilon = \left| \frac{\left[\Pi(1) - \Pi(0)\right] - \int_0^1 \left\{ -\left[\frac{1}{XV}\frac{\partial V}{\partial n}\right] P U_s^2 + \left[\frac{1}{XR}\frac{\partial R}{\partial n}\right] P U_\phi^2 \right\} d_z}{\left[\Pi(1) - \Pi(0)\right]} \right| \quad (1)$$

## Function FAMACH (AN)

<u>Object</u> Calculate Mach number from velocity

<u>Variables</u>

| | | |
|---|---|---|
| AN | $V/C_o$ | Velocity/stagnation speed of sound |
| FAMACH | M | Mach number |

<u>Theory</u>

The Mach number can be calculated from

$$\frac{V}{C_o} = M/(1 + \frac{r-1}{2} M^2)^{1/2} \qquad (1)$$

using Newton's method.

Subroutine FAVER2

Object  Solve for mass flow weighted average flow and output parameters.

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| AAR | = | AR | , Area ratio (dimensionless) |
| AMA | = | M | , Local Mach number (dimensionless) |
| AMACHE | = | $\tilde{M}$ | , Area average Mach number (dimensionless) |
| AMFH | = | $(G\mathring{M}/V)_H$ | , Wall bleed hub (dimensionless) |
| AMFT | = | $(G\mathring{M}/V)_T$ | , Wall bleed tip (dimensionless) |
| AMG | = | $M_{MID}$ | , Midpoint Mach number (dimensionless) |
| AMM | = | $M_{MAX}$ | , Maximum Mach number (dimensionless) |
| ASH | = | $A_{SH}$ | , Surface area hub wall (dimensionless) |
| AST | = | $A_{ST}$ | , Surface area tip wall (dimensionless) |
| ATFH | = | $(GQ/V)_H$ | , Heat flux/length hub (dimensionless) |
| ATFT | = | $(GQ/V)_T$ | , Heat flux/length tip (dimensionless) |
| CFHϕ | = | ${C_{FH}}^J$ | , Wall friction coefficient hub (dimensionless) |
| CFTϕ | = | ${C_{FT}}^J$ | , Wall friction coefficient tip (dimensionless) |
| ϕ | = | 1,2,3 for J+1-ϕ station | |
| CPC | = | $Pr/q_1$ | , Normalizing factor for $C_p$ dimensionless |
| CPCØMP | = | $C_{PC}$ | , Pressure coefficient (compressible) (dimensionless) |
| CPJNC | = | $C_{PI}$ | , Pressure coefficient(incompressible) (dimensionless) |
| DASH1,DASH2 | = | $\Delta A_{SH}$ | , Area increment hub (dimensionless) |

| | | | |
|---|---|---|---|
| DAST1,DAST2 | = | $\Delta A_{ST}$ | , Area increment tip (dimensionless) |
| DENTP1, DENTP2 | = | $\Delta\bar{I}$ | , Change in entropy (dimensionless) |
| DISP | = | $\bar{\Phi}$ | , Dissipation function (dimensionless) |
| DPSTI1, DPSTI2 | = | $\Delta\bar{\psi}$ | , Increment in mass flow (dimensionless) |
| DQSH1, DQSH2 | = | $\Delta\tilde{Q}_{T_H}$ | , Increment in heat flow hub (dimensionless) |
| DQST1, DQST2 | = | $\Delta\tilde{Q}_T$ | , Increment in heat flow tip (dimensionless) |
| DTHEO1 DTHEO2 | = | $\Delta\bar{\Theta}_o$ | , Increment in total temperature (dimensionless) |
| PIO | = | $\Pi_o$ | , Average total pressure (dimensionless) |
| PIOO | = | $\Pi_{oo}$ | , Average inlet total pressure (dimensionless) |
| PSI | = | $\bar{\psi}$ | , Mass flow (dimensionless) |
| PSIO | = | $\bar{\psi}_o$ | , Initial mass flow (dimensionless) |
| QM | = | $1/2(\rho U^2)_{MAX}$ | , Free stream dynamic pressure (dimensionless) |
| QSH | = | $\tilde{Q}_H$ | , Total heat flow hub (dimensionless) |
| QST | = | $\tilde{Q}_T$ | , Total heat flow tip (dimensionless) |
| RØM | = | $\rho_{max}$ | , Free stream density (dimensionless) |
| RUM | = | $(\rho U)_{MAX}$ | , Maximum momentum (dimensionless) |
| THEO | = | $\bar{\Theta}_o$ | , Average total temperature (dimensionless) |
| THEOO | = | $\bar{\Theta}_{oo}$ | , Inlet average total temperature (dimensionless) |
| UM | = | $U_{MAX}$ | , Free stream velocity (demensionless) |

Theory

The mass flow weighted average quantity $\bar{\phi}$ is defined by

$$\bar{\phi} = \frac{1}{\bar{\Psi}} \int_0^1 \frac{GPU_S}{V} \phi \, dn \tag{1}$$

where

$$\bar{\Psi} = \int_0^1 \frac{GPU_S}{V} dn \tag{2}$$

The area is given by

$$A = \int_0^1 \frac{G}{V} dn \tag{3}$$

It is noted that the mass flow weighted averages satisfy certain conditions

$$\frac{d\bar{\Psi}}{dS} = \left(\frac{G\mathring{M}}{V}\right)_T + \left(\frac{G\mathring{M}}{V}\right)_H \tag{4}$$

$$\frac{d}{dS}(\bar{\Psi}\bar{\Theta}_0) = \left[\frac{G\mathring{M}\Theta_0}{V}\right]_T + \left[\frac{G\mathring{M}\Theta_0}{V}\right]_H - \frac{\gamma}{\gamma-1}\left[\left(\frac{GQ}{V}\right)_T - \left(\frac{GQ}{V}\right)_H\right] \tag{5}$$

The entropy is related to the dissipation by

$$\frac{d}{dS}(\Psi\bar{I}) = \left(\frac{G\mathring{M}I}{V}\right)_T + \left(\frac{G\mathring{M}I}{V}\right)_H + \gamma M_r \int_0^1 \frac{G}{\Theta V^2}\left[\Sigma_{ns}E_{ns} + \Sigma_{n\phi}E_{n\phi} + \Phi_R\right] dn$$
$$- \frac{\gamma}{\gamma-1}\int_0^1 \frac{GQ}{V\Theta^2}\frac{d\Theta}{dn} dn - \frac{\gamma}{\gamma-1}\left[\left(\frac{GQ}{V\Theta}\right)_T - \left(\frac{GQ}{V\Theta}\right)_H\right] \tag{6}$$

Equation (4) states that the change in mass flow is the net flow crossing the wall boundary. Equation (5) states that the change in total energy flux is the net crossing the boundary walls. Thus, for an adiabatic wall, the mass flow weighted average total temperature is constant. Finally, equation (6) states that the change in entropy flux is the net crossing the boundary plus the change due to the dissipation function and heat fluxes. Then using the definition of entropy we have

$$\frac{\bar{\Pi}_{02}}{\bar{\Pi}_{01}} = \left(\frac{\bar{\Theta}_{02}}{\bar{\Theta}_{01}}\right)^{\frac{\gamma}{\gamma-1}} \exp\left[\bar{I}_2 - \bar{I}_1\right] \tag{7}$$

and the loss coefficient is given by

$$C_{PL} = \frac{\bar{P}_{01} - \bar{P}_{02}}{\bar{P}_{01} - \bar{P}_1} = \frac{1 - P_{02}/\bar{P}_{01}}{1 - \bar{P}_1/\bar{P}_{01}} = \frac{1 - \bar{\Pi}_{02}/\bar{\Pi}_{01}}{1 - \bar{\Pi}_1/\bar{\Pi}_{01}} \tag{8}$$

If we now defined the mass flow weighted averages

$$\bar{\Pi}_o = a_r \int_0^1 \frac{G}{V} \frac{\Pi^2}{\sqrt{\Theta}} M \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} dn \tag{9}$$

$$\bar{\Theta}_o = a_r \int_0^1 \frac{G}{V} \pi \sqrt{\Theta}\, M \left(1 + \frac{\gamma-1}{2} M^2\right) dn \tag{10}$$

$$\bar{\Psi} = a_r \int_0^1 \frac{G}{V} \frac{\pi}{\sqrt{\Theta}} M\, dn \tag{11}$$

This subroutine also calculates some quantities printed in the summary at the end of the viscous calculation.

The pressure coefficient is defined by

$$\bar{C}_P = \frac{\bar{\Pi} - \bar{\Pi}_1}{\bar{\Pi}_{01} - \bar{\Pi}_1} \tag{12}$$

An effective area $\tilde{A}$ can be defined as the geometrical area minus the blockage caused by the boundary layer. If we define the freestream as the point of maximum velocity across the duct we have by definition

$$\rho_\infty U_\infty A_{eff} = \mathring{m} = (\Psi_T - \Psi_H) N_B \tag{13}$$

Hence, the blockage B is defined as

$$B = 1 - A/A_{eff} = 1 - m/(\rho_\infty U_\infty A) \tag{14}$$

The area averaged (effective Mach number) may then be defined by the isentropic flow relations. Thus,

$$\frac{A_{eff}}{A} = \frac{M_{eff}}{M} \left[\frac{1 + \frac{\gamma-1}{2} M_\infty^2}{1 + \frac{\gamma-1}{2} M_{eff}^2}\right]^{\frac{1}{2}\frac{\gamma+1}{\gamma-1}} \tag{15}$$

The effectiveness $\eta$ of the diffuser is based on an ideal isentropic flow with the mass flow weighted average Mach numbers. Thus, the ideal pressure coefficient is given by

$$C_{PI} = \frac{\tilde{\Pi} - \bar{\Pi}_1}{\bar{\Pi}_{01} - \bar{\Pi}_1} \tag{16}$$

where

$$\frac{\Pi_{01}}{\tilde{\Pi}} = \left[1 + \frac{\gamma - 1}{2}\tilde{M}^2\right]^{\frac{\gamma}{\gamma-1}} \tag{17}$$

$$\frac{A}{A_1} = \frac{\bar{M}_1}{\tilde{M}}\left[\frac{1 + \frac{\gamma-1}{2}\tilde{M}^2}{1 + \frac{\gamma-1}{2}\bar{M}_1^2}\right]^{\frac{1}{2}\frac{\gamma+1}{\gamma-1}} \tag{18}$$

Then

$$\eta = \bar{C}_p / C_{PI} \tag{19}$$

The wall friction coefficient is defined as

$$C_f = \Sigma w \Big/ \left(\frac{1}{2}\rho u^2\right)_{MAX} \tag{20}$$

The wall surface area and heat flow are determined by integrating the equations

$$A_S = \int_0^S \frac{2\pi R}{V}\, dS \tag{21}$$

$$\tilde{Q}_S = \int_0^S \frac{2\pi R Q}{V}\, dS \tag{22}$$

using the trapezoid rule.

## Function FCØLES (Argument List)

Object   Compute Coles velocity profile for boundary layer at initial station.

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| AK | = | $K$ | , Von Karman constant |
| APLS | = | $A^+$ | , Van Driest constant |
| API | = | $M$ | , Coles shape factor |
| AKPL | = | $K_S^+$ | , Roughness Reynolds number |
| DELT | = | | , Boundary layer thickness |
| DAMP | = | $D$ | , Damping factor |
| PI | = | $\pi$ | , 3.14159 |
| Y | = | $Y$ | , Distance from wall |
| YPLUS | = | $Y^+$ | , Universal distance |
| UPLUS | = | $U^+$ | , Universal velocity |
| FCØLES | = | $U_c^+$ | , Coles velocity (output) |

Theory

This subroutine integrates the differential equation for the inner layer given by

$$\frac{dU^+}{dy^+} = \frac{2}{1+\left[1+4K^2 y^{+2} D^2\right]^{1/2}} \tag{1}$$

with the damping factor, references (7, 8), given by

$$D = 1 - \exp\left(-\frac{Y^+}{A^+}\right) + \left(1 + \frac{K_S^+}{30\,Y^+}\right)\exp\left(-2.3\,\frac{Y^+}{K_S^+}\right) \tag{2}$$

and adds Coles' wake function (reference 3), given by

$$U_c^+ = U^+ + 2\,\frac{\tilde{\pi}}{K}\,\sin^2\left(\frac{\pi}{2}\,\frac{Y}{\delta}\right) \tag{3}$$

## Subroutine FCØRCT

<u>Object</u> Correct truncation error

<u>Options</u> None

<u>List of Symbols</u>

| | | | |
|---|---|---|---|
| AMUW | = | $\mu w/M$ | , Wall value of viscosity (dimensionless) |
| DU | = | $\Delta U$ | , Velocity difference (dimensionless) |
| ECØR | = | $(\rho U)/(\rho U)_m$ | , Mass flux ratio (dimensionless |
| EMB | = | $E_m$ | , Error in Mach number (dimensionless) |
| EPB | = | $E_p$ | , Error in static pressure (dimensionless) |
| ERB | = | $E_R$ | , Error in density (dimensionless) |
| ETB | = | $E_T$ | , Error in static temperature (dimensionless) |
| EUB | = | $E_U$ | , Error in velocity (dimensionless) |
| EUP | = | $E_{U\emptyset}$ | , Error in swirl velocity (dimensionless) |
| EUS | = | $E_{US}$ | , Error in streamwise velocity (dimensionless) |
| EW | = | $E_w$ | , Strain |

<u>Theory</u>

The point-to-point instability described in reference 6 is minimized by recalculating the stresses and heat flux using central differences rather than centered differences.

## Subroutine FCPLX

Object  Evaluates complex functions for exact coordinate calculation.

Options

LØPT = 1  Compute and store functions and derivatives
LØPT = 2  Compute only derivatives

List of Symbols  (Note subscript notation for derivatives used)

| | | |
|---|---|---|
| N1,N2 | = | $N_1, N_2$ |
| XS | = | $S$ |
| XN | = | $n$ |
| XSX | = | $S_x = n_y$ |
| XSY | = | $S_y = n_x$ |
| XD | = | $D$ |
| XZETS | = | $\xi_S = \eta_n$ |
| XETAS | = | $\eta_s = -\xi_n$ |
| XXS | = | $x_s = y_n$ |
| XYS | = | $y_s = x_n$ |
| XB1 | = | $\tilde{X} = \xi_x = \eta_y$ |
| YB1 | = | $\tilde{Y} = -\xi_y = \eta_x$ |
| X1 | = | $x$ |
| Y1 | = | $y$ |
| XDB | = | $\bar{D}$ |
| XNZET | = | $n_\xi$ |
| XNETA | = | $n_\eta$ |
| XV | = | $V$ |

| | | |
|---|---|---|
| XSXX | = | $S_{xx} = n_{xx} = s_{yy}$ |
| XSXY | = | $S_{xy} = n_{yy} = n_{xx}$ |
| XXSS | = | $X_{ss} = y_{ns} = x_{nn}$ |
| XXSN | = | $X_{sn} = y_{nn} = -y_{ss}$ |
| XB2 | = | $\approx X = \xi_{xx} = \eta_{yx} = -\xi_{xy}$ |
| YB2 | = | $\approx Y = -\xi_{xy} = -\eta_{yy} = \eta_{xx}$ |
| XZSS | = | $\xi_{ss} = \eta_{sn} = -\xi_{nn}$ |
| XZSN | = | $\xi_{sn} = \eta_{nn} = -\eta_{ss}$ |
| XDBN | = | $\bar{D}_n$ |
| XDBS | = | $\bar{D}_s$ |
| XESDN | = | $(\eta_s/\bar{D})_n$ |
| XESDN | = | $(\eta_s/\bar{D})_s$ |
| XZSDN | = | $(\xi_s/\bar{D})_n$ |
| XZSDS | = | $(\xi_s/\bar{D})_s$ |
| XVN | = | $V_n$ |
| XVS | = | $V_s$ |
| XESS | = | $\eta_{ss}$ |
| XESN | = | $\eta_{sn}$ |
| XDIS | = | $D_s$ |
| XDIN | = | $D_n$ |

Theory

The theory for evaluating the complex functions and all derivatives is derived in reference (6). With the use of orthogonality relations which are implicit in the theory of complex function, the functions and derivatives may be evaluated. It is noted that this subroutine was programmed to accept multiple sources in the z plane, although only one is used in the present calculation. The derived functions calculated in this subroutine are listed as follows:

$$S = \sum_{I=1}^{NS} \frac{A_I}{2} \ln\left[(X-b_I)^2 + y^2\right] \tag{1}$$

$$n = \sum_{I=1}^{NS} A_I \tan^{-1}\left[y/(X-b_I)\right] \tag{2}$$

$$S_x = \sum_{I=1}^{NS} \frac{A_I\,(X-b_I)}{\left[(X-b_I)^2 + y^2\right]} \tag{3}$$

$$S_y = \sum_{I=1}^{NS} \frac{A_I\,y}{\left[(X-b_I)^2 + y^2\right]} \tag{4}$$

$$S_{xx} = \sum_{I=1}^{NS} \frac{A_I}{\left[(X-b_I)^2 + y^2\right]} \left\{1 - \frac{2(X-b_I)^2}{\left[(X-b_I)^2 + y^2\right]}\right\} \tag{5}$$

$$S_{yy} = -\sum_{I=1}^{NS} \frac{A_I\,2y(X-b_I)}{\left[(X-b_I)^2 + y^2\right]} \tag{6}$$

$$D = -(S_x^2 + S_y^2) \tag{7}$$

$$X_s = -S_x/D \tag{8}$$

$$Y_s = -S_y/D \tag{9}$$

$$\xi_s = \xi_x X_s + \xi_y Y_s \tag{10}$$

$$\eta_s = \eta_x X_s + \eta_y Y_s \tag{11}$$

$$V = \frac{1}{\left[\xi_s^2 + \xi_n^2\right]^{1/2}} \tag{12}$$

$$D_s = -\left[2 S_y (S_{yx} X_s + S_{yy} Y_s) + 2 S_x (S_{xx} X_s + S_{xy} Y_s)\right] \tag{13}$$

$$D_n = -\left[2 S_y (S_{yx} X_n + S_{yy} Y_n) + 2 S_x (S_{xx} X_n + S_{xy} Y_n)\right] \tag{14}$$

$$X_{ss} = -\left[\frac{S_{xx} X_s + S_{xy} Y_s}{D} - \frac{S_x D_s}{D^2}\right] \tag{15}$$

$$X_{sn} = -\left[\frac{(S_{xx} X_n + S_{xy} Y_n)}{D} - \frac{S_x D_n}{D^2}\right] \tag{16}$$

$$\xi_{ss} = \xi_x X_{ss} + \xi_{xx} X_s^2 + 2\xi_{xy} Y_s X_s + \xi_y Y_{ss} + \xi_{yy} Y_s^2 \tag{17}$$

$$\xi_{sn} = \xi_x X_{sn} + \xi_y Y_{sn} + (\xi_{yy} - \xi_{xx}) Y_s X_s + \xi_{xy} (X_s^2 - Y_s^2) \tag{18}$$

$$V_s = -V^3/\left[\xi_s \xi_{ss} + \xi_n \xi_{ns}\right] \tag{19}$$

$$V_n = -V^3/\left[\xi_s \xi_{sn} + \xi_n \xi_{nn}\right] \tag{20}$$

Numerical accuracy can be significantly improved by ordering the way in which sums and products are made. As an example, the first equation, equation (1), may be written

$$S = \sum_{I=1}^{NS} A_I \left\{ |X - b_I| \left[1 + \left(\frac{y}{X - b_I}\right)^2\right]^{1/2} \right\} \qquad |X - b_I| > |y|$$

$$= \sum_{I=1}^{NS} A_I \left\{ |y| \left[1 + \left(\frac{X - b_I}{y}\right)^2\right]^{1/2} \right\} \qquad |y| > |X - b_I|$$

Thus the square root of the sum of squares of O(1) and $S = O(|Y - b_I|)$. This rule has been applied to all equations by extracting the order of magnitude of the term from each calculation.

Subroutine FETA (B, ETA, AN, DEDN, D2EDN)

Object

Calculate distorted mesh to be used in Subroutine PØIS

Options

| | |
|---|---|
| B = 0 | Uniform mesh (no stretching) |
| B > 0 | Tanh stretching |

Variables

| | | |
|---|---|---|
| B | | , Constant |
| ETA | $\eta$ | , Transformed Normal Coordinate |
| AN | $n$ | , Normal Coordinate |
| DEDN | $\partial\eta/\partial n$ | |
| D2EDN | $\partial^2\eta/\partial n^2$ | |

Theory

This subroutine calculates the distorted mesh that will be used in calculation by subroutine PØIS. The transformation is given by

$$\left.\begin{aligned} \eta &= \tanh[Bn]/\tanh[B] \quad & B > 0 \\ \eta &= n & B = 0 \end{aligned}\right\} \tag{1}$$

Subroutine FINTG (IKL)

Object    Integrate equations for potential flow.

Options

IKL = Number of streamlines

List of Symbols

IKL    , Number of streamlines

Theory

Four simultaneous ordinary differential equations are integrated using a third order Runge-Kutta numerical integration method. These equations are given in FCPLX and denoted as

$$\left.\begin{aligned} \frac{dX}{dS} &= X_S(X,Y) \\ \frac{dY}{dS} &= Y_S(X,Y) \\ \frac{d\xi}{dS} &= \xi_S(X,Y) \\ \frac{d\eta}{dS} &= \eta_S(X,Y) \end{aligned}\right\} \qquad (1)$$

The Runge-Kutta formulas applied to the first equation are

$$\left.\begin{aligned} B_{11} &= \Delta S X_S(X,Y) \\ B_{12} &= \Delta S X_S(X+B_{11}/2\ ,Y+B_{21}/2) \\ B_{13} &= \Delta S X_S(X+2B_{12}-B_{11}\ ,\ Y+2B_{22}-B_{21}) \end{aligned}\right\} \qquad (2)$$

$$X(S+\Delta S) = X(S) + (B_{11} + 4B_{12} + B_{13})/6 \qquad (3)$$

## Subroutine FLØWIN

<u>Object</u> Setup inlet flow.

<u>Options</u>

IØPT1 = 1 Compute inlet flow
If ($T_o$=0) $P_o=P_r$ and $T_o=T_r$

IØPT1 = 2 Read inlet flow
If ($T_o$>10.) Normalize with $T_r$ and $P_r$

<u>List of Symbols</u>

BINP(I,J,K) , Interpolated from BINPUT(IH,J,L)

<u>Theory IØPT1=1</u>

For this option the freestream flow is assumed to be isentropic with a constant freestream Mach number $M_s$ and wall boundary layers defined by power-law velocity profiles. Since the swirling flow must be in radial equilibrium, the normal momentum equations must be satisfied together with isentropic relationships of pressure ratio and temperature ratio.

Neglecting curvature in the meridional plane

$$\frac{\partial \Pi}{\partial n} = \frac{\gamma}{R} \frac{\partial R}{\partial n} \Pi M_\phi^2 \tag{1}$$

where

$$M_\phi^2 = M^2 - M_s^2 \tag{2}$$

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{\Pi_0}{\Pi}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{3}$$

Equation (1) can be integrated with

$$M(0) = M_s/\cos(\alpha_H) \tag{4}$$

and

$$\frac{\Pi_0}{\Pi(0)} = \left[1 + \frac{\gamma-1}{2} M(0)^2\right]^{\frac{\gamma}{\gamma-1}} \tag{5}$$

as initial conditions using a Runge-Kutta method.

For a given displacement thickness and velocity profile power law, wall boundary layers can be added, assuming collateral boundary layers, such that $\alpha$ is unchanged. Then

$$\Delta = (1+n)\Delta^* \tag{6}$$

$$\frac{U}{U_\infty} = \left(\frac{y}{\Delta}\right)^{1/n_2} \tag{7}$$

and

$$\frac{\Theta}{\Theta_\infty} = 1 + \sqrt[3]{P_{RL}}\ \frac{\gamma-1}{2} M_\infty^2 \left[1 - \left(\frac{U}{U_\infty}\right)^2\right] + \frac{\Theta_W - \Theta_{AW}}{\Theta_\infty}\left[1 - \frac{U}{U_\infty}\right] \tag{8}$$

Finally, the inlet mass flow and reference velocity are determined as follows

$$u_r = \frac{N_B}{A}\int_0^1 \frac{G}{V} P U_s \frac{d\eta}{X} \tag{9}$$

$$\overset{\circ}{w} = g \rho_r u_r a_r A \tag{10}$$

Theory IØPT1=2

For this option, the input flow is calculated from experimental input data. The input variables selected are spanwise location, total pressure, static pressure, flow angle, and total temperature, since these are the primary measured variables. A simple linear interpolation is used so that for any variable $\phi$,

$$\phi(Y(\eta)) = \phi(Y_1) + \left[\phi(Y_2) - \phi(Y_1)\right]\left[Y(\eta) - Y_1\right] \tag{11}$$

The flow variables are calculated from equations 1 through 7.

If ($T_\infty > 10$), it is assumed that pressure and temperature are given in (psf) and deg R, respectively, and the flow is normalized accordingly. If $\delta^*$ is given, it is assumed that boundary layers should be added accordingly to the velocity profile power law above. Finally, the weight flow and reference velocity are determined from equations 9 and 10. A flow chart of this subroutine is presented in figure 20.

## Subroutine FNØRM

<u>Object</u> Normalize input variables .

<u>Options</u>

None

<u>List of Symbols</u>

All variables in CØMMØN blocks

<u>Theory</u>

All input variables are normalized according to the List of Symbols.

## Subroutine FØRCE/PRØP

Object    Compute blade forces

Options

| | |
|---|---|
| NØPPF = 1 | Radial, axial, and swirl blade forces are defined in propeller portion of program. |
| NØPPF = 0 | Radial, axial, and swirl blade forces are read from input. |

List of Symbols

| | |
|---|---|
| FRCI(N, 1) | Blade force (radial direction)/span |
| FRCI(N, 2) | Blade force (phi direction)/span (dimensionless) |
| FRCI(N, 3) | Blade force (axial direction)/span (nondimension) |
| FRC(N, 1) | Blade force (radial direction)/span (nondimension) |
| FRC(N, 2) | Blade force (phi direction)/span (nondimension) |
| FRC(N, 3) | Blade force (axial direction)/span (nondimensional) |
| FØRC(3, K) | Blade force (stream direction)/volume (nondimensional) |
| FØRC(4, K) | Blade force (swirl)/volume (nondimensional) |
| FLØC(5, N) | cosine of $\theta$ |
| FLØC(6, N) | sine of $\theta$ |
| K | Index of $\eta$ coordinate |
| N | Index of points along propeller centerline |

Theory

This subroutine is used to calculate the streamwise and swirl blade components for each streamline. It is assumed that the normal component is small. The process has two steps.

(1st) Calculation of radial, axial, and phi blade force components for each streamline by using linear interpolation of blade points.

(2nd) Converting radial, axial, phi blade force components to streamwise and swirl blade forces.

## Subroutine FØRCL

<u>Object</u> Compute local blade force.

<u>Options</u> None

<u>List of Symbols</u>

| | | |
|---|---|---|
| GAP | $= G$ | , Strut gap (dimensionless) |
| ZLE | $= Z_{LE}$ | , Location of leading edge (dimensionless) |
| ZTE | $= Z_{TE}$ | , Location of trailing edge (dimensionless) |

<u>Theory</u>

The chordwise distribution of blade loading (force/volume) is defined by

$$q_s = \frac{\mu_E}{P_{r_T}} V \frac{\partial}{\partial S}(C_p T) \tag{1}$$

$$q_\phi = \frac{\mu_E}{P_{r_T}} \frac{1}{r} \frac{\partial}{\partial \phi}(C_p T) \tag{2}$$

$$I - I_r = C_p \ln\left(\frac{T}{T_r}\right) - \ln\left(\frac{P}{P_r}\right) \tag{3}$$

In this subroutine, the chordwise loading is assumed uniform.

## Function FTHIK (Z,IS,LØP)

Object  Compute blade thickness distribution.

Options

IS=1  NASA 5 digit series distribution.
IS=4  Input thickness distribution.
IS=7  65-A series thickness distribution.
LØP=1  FTHIK = $t/t_{max}$
LØP=2  FTHIK = $d\ (t/t_{max})/d(x/c)$

List of Symbols

$Z = x/c$ , Fractional chordwise distance.

FTHIK = $t/t_{max}$ , Ratio of thickness to maximum thickness of blade.

Theory

A thickness distribution of the form

$$t/t_{max} = 1.4845\ Z^{\frac{1}{2}} - .63\ Z - 1.758Z^2 + 1.4215\ Z^3 - .5075Z^4 \qquad (1)$$

is used to representa a NASA 5 digit series distribution (IS=1).

For a NASA 65A series distribution or for any arbitrary distribution (IS=4) table data is used to represent the distribution.

Subroutine GBLADE

Object Compute Blade Geometry

Options None

List of Symbols

| | | |
|---|---|---|
| ALPHS | $\alpha$ | , Stagger angle to axis (deg) |
| CHRD | B | , (Local) blade chord (dimensionless) |
| GAP | G | , Gap between blades (dimensionless) |
| IRT | | , Index Counter |
| ISHAPE | | , Blade shape (Option) |
| NBLADE | | , Number of blades in one row |
| NRW | | , Number of blade rows |
| NUM | | , Number of points along blade centerline |
| PHIC | $\phi_c$ | , Blade camber |
| RCLH | $R_{CLH}$ | , Hub radius of blade centerline |
| RCLT | $R_{CLT}$ | , Tip radius of blade centerline |
| SLD | $\sigma$ | , Solidity |
| THICK | t | , Local blade thickness |
| THICKN | $t_n$ | , Blade thickness |
| THIKM | t/B | , Maximum thickness/chord |
| ZBAR | $\bar{Z}$ | , Axial position with respect to blade |
| ZCL | $Z_{CL}$ | , Blade axial centerline |
| ZCLX | $Z_{CLX}$ | , Axial distance to blade centerline |
| ZKK | | , Fractional distance along chordline |
| ZLE | $Z_{LE}$ | , Blade leading edge |

| | | |
|---|---|---|
| ZTE | $Z_{TE}$ | , Blade trailing edge |
| CONST(1, L) | $R_L$ | , Radius (input data) |
| CONST(2, L) | $\alpha_L$ | , Stagger angle (input data) |
| CONST(3, L) | $B_L$ | , Chord (input data) |
| CONST(4, L) | $(t/B)_L$ | , Thickness to chord ratio (input data) |
| CONST(5, L) | $\phi_L$ | , Camber angle (input data) |
| CONST(6, L) | $Z_{CL}$ | , Axial distance (input data) |
| Q(2, L) | R | , Radius |
| Q(13, L) | G | , Gap |
| Q(14, L) | $\partial G/\partial n$ | , Normal derivative of blade surface |
| Q(15, L) | $\partial G/\partial S$ | , Streamwise derivative of blade surface |

Theory

This module interpolates blade data with respect to the radius of blades in order to obtain local blade information. The following parameters are interpolated; $\alpha$, B, t/B, $\phi_c$, and $Z_{CLX}$. The blade thickness is then calculated in FTHIK and used to determine G, $\partial G/\partial n$ and $\partial G/\partial s$. A flow chart is given in Fig. 21.

## Subroutine GDUCT

Object    Compute Duct shape

Options

IØPT3=1  Straight annular duct
IØPT3=2  Read duct shape
IØPT3=3  Straight-wall diffuser
IOPT3=4  NACA curved-wall diffuser

List of Symbols

(As needed by user)

Theory

This subroutine is used to prescribe the duct shape $r_H(Z)$, $r_T(Z)$, wall bleed $\overset{o}{m}_H(Z)$, $\overset{o}{m}_T(Z)$, and wall temperature $T_H(Z)$, $T_T(Z)$, as required. Since these functions are input, the programmer may write a subroutine for this purpose or read the required information according to IØPT3. In addition, the subroutine computes the reference radius and normalizes the variables r and T. The variable $\overset{o}{m}$ is normalized in Subroutine FLØWIN when $U_r$ is calculated.

Input/Output

The user may program any duct shape and wall boundary conditions as required. The output of this subroutine must be (R(I,K,J), I=1,3; K=1,2, J=1,JL) and Z1. Note that all variables are normalized as shown in the sample subprogram described in the Subroutine GDUCT listing and that equally spaced spanwise stations are used. The flowchart (figure 22) should be followed in programming.

## Subroutine GEØMCL

Object Calculate coordinates of lifting line.

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| AL | = | $A_L$ | , Slope of lifting line |
| AM | = | $A_M$ | , Slope of coordinate line |
| AN1, AN2 | = | $N_1$, $N_2$ | , N coordinate of grid |
| ANI, ANI1 | = | $N_I$, $N_{I-1}$ | , N coordinate of lifting line intersection with grid |
| ANL | = | $N_L$ | , N coordinate of input point of lifting line |
| R1, R2 | = | $R_1$, $R_2$ | , R coordinate of grid line |
| RI, RI1 | = | $R_I$, $R_{I-1}$ | , R coordinate of lifting line intersection with grid |
| RL | = | $R_L$ | , R coordinate of lifting line input |
| S1, S2 | = | $S_1$, $S_2$ | , S coordinate of grid |
| SI, SI1 | = | $S_I$, $S_{I-1}$ | , S coordinate of lifting line intersection with grid |
| SSL | = | $S_L$ | , S coordinate of lifting line input point |
| Z1, Z2 | = | $Z_1$, $Z_2$ | , Z coordinate of grid line |
| ZI, ZI1 | = | $Z_I$,$Z_{I-1}$ | , Z coordinate of lifting line intersection with grid |
| CONS(1,L) | = | $R_L$ | , Lifting line radius (Local) |
| CONS(2,L) | = | $\alpha_L$ | , Stagger angle (Local) |
| CONS(3,L) | = | $B_L$ | , Chord (Local) |
| CONS(4,L) | = | $(t/B)_L$ | , Thickness/chord (local) |
| CONS(6,L) | = | $Z_{CL}$ | , Lifting Line Axial Distance (local) |

| | | |
|---|---|---|
| CONS(8,L) | $n_L$ | Lifting line normal locations |
| CONS(9,L) | $S_L$ | Lifting line streamwise location |

Theory

The equation for the lifting line passing through the points (L, L-1) is approximated by a line given by

$$Z = Z_{L-1} + A_L(R - R_{L-1}) \tag{1}$$

where the slope is given by

$$A_L = (Z_L - Z_{L-1})/(R_L - R_{L-1}) \tag{2}$$

The streamline coordinate system forms a box around the L-1 mesh point (see figure 23) given by the points (1), (2), (3), (4). If it is assumed that point (5) is known; the object is to find point (6) by successively checking each side of the mesh to determine if the lifting line crosses. Let the index I = 1, 4 represent each side of the box. Then a straight line is passed through the pair of points

| I | Points | |
|---|---|---|
| 1 | (2), (1) | $n_1$ - S varies |
| 2 | (3), (2) | $S_2$ - n varies |
| 3 | (4), (3) | $n_2$ - S varies |
| 4 | (1), (4) | $S_1$ - n varies |

The equation of the straight line approximating the lifting line is given by

$$Z = Z_1 + A_M \cdot (R - R_1)$$
$$A_M = (Z_2 - Z_1)/(R_2 - R_1) \tag{3}$$

Then the intersection of the lifting line with the coordinate line is given by

$$R_I = (Z_{L-1} - A_L \cdot R_{L-1} - Z_1 + A_M R_1)/(A_M - A_L) \tag{4}$$

$$Z_I = [(Z_{L-1} - A_L \cdot R_{L-1}) \cdot A_M - (Z_1 - A_M \cdot R_1) \cdot A_L]/(A_M - A_L) \tag{5}$$

provided

$$A_M - A_L \neq 0 \tag{6}$$

From figure (23) R,Z will intersect inside the mesh if:

$$R_1 \leq R_I \leq R_2 \text{ or } R_2 \leq R_I \leq R_1 \tag{7}$$

and

$$Z_1 \leq Z_I \leq Z_2 \text{ or } Z_2 \leq Z_I \leq Z_1 \tag{8}$$

For I = 1 and 3, n is constant and S varies. Thus

$$\begin{aligned} S_I &= S_1 + (R_I - R_1)/(R_2 - R_1)\,(S_2 - S_1) \\ n_I &= n_1 \text{ if } I = 1 \\ n_I &= n_2 \text{ if } I = 3 \end{aligned} \tag{9}$$

Likewise for I = 2 and 4, S is constant and n varies. Thus

$$\begin{aligned} n_I &= n_1 + (R_I - R_1)/(R_2 - R_1)\,(n_2 - n_1) \\ S_I &= S_2 \text{ if } I = 2 \\ S_I &= S_1 \text{ if } I = 4 \end{aligned} \tag{10}$$

Then $R_I$, $Z_I$, $S_I$, $n_I$ is known for point (6)

From figure 18, it can be seen that if

$$R_{I-1} \leq R_L \leq R_I \tag{11}$$

$R_L$ lies within the grid (1), (2), (3), (4), and L should be advanced. Both n and S vary along the lifting line. If ($R_L$, $Z_L$) lies within the grid then $n_L$, $S_L$ can be determined by the relations

$$S_L = S_I + (S_I - S_{I-1})/(R_I - R_{I-1})\ (R_L - R_{L-1})$$
$$n_L = n_{I-1} + (n_I - n_{I-1})/\ (R_I - R_{I-1})\ (R_L - R_{L-1}) \qquad (12)$$

This procedure can then be repeated for L = 2, NUM

## Subroutine INITQ

Object

Initialize data file parameters for Q array

Option

None

Variables

| | | |
|---|---|---|
| BLOCK(1) | JSTEP | , Block (record number) |
| Q(1,K) | R | , Radius (dimensionless) |
| Q(2,K) | Z | , Axial distance (dimensionless) |
| Q(3,K) | $\partial R/\partial n$ | , Derivative |
| Q(4,K) | $\partial R/\partial s$ | , Derivative |
| Q(5,K) | $(\cos\theta)^2_{axi}$ | , Axisymmetric flow angle |
| Q(6,K) | V | , Metric coefficient (dimensionless) |
| * Q(7,K) | $\partial V/\partial n = (K_s + \Delta K_s)$ | , Curvature of streamline |
| Q(8,K) | $\partial V/\partial s$ | , Curvature of potential line |
| Q(9,K) | X | , Distance along streamline (dimensionless) |
| Q(10,K) | Y | , Duct height (dimensionless) |
| Q(11,K) | $Y/Y_T$ | , Normalized duct height |
| Q(12,K) | A | , Duct Area (dimensionless) |
| Q(13,K) | G | , Gap (dimensionless) |
| Q(14,K) | $\partial G/\partial n$ | , Derivative |
| Q(15,K) | $\partial G/\partial s$ | , Derivative |
| Q(16,K) | $\partial \eta/\partial n$ | , Transformation of normal coordinate |

Variables (Cont'd)

| | | |
|---|---|---|
| Q(17,K) | | , Not used |
| Q(18,K) | n | , Normal coordinate (dimensionless) |
| Q(19,K) | $\eta$ | , Transformed coordinate |
| | K = 1, KL | |
| QPARM(1) | $r_r$ | , Reference radius, (ft) |
| QPARM(2) | | , Not used |
| QPARM(3) | JL | , Number of streamwise steps |
| QPARM(4) | KL | , Number of streamlines |

Theory

This subroutine initializes the independent variable array BLOCK which is stored on a disc file and sets all parameters QPARM required by the calculation.

* Note that Q(7,K) stores either $K_s$ or $K_s+\Delta K_s$.

## Subroutine INTFRE

Object

Initialize freestream conditions

Options

None

List of Symbols

See CØMMØN BLØCKS

Theory

Data read from file NDRUM is used to set up the freestream conditions for subroutine PØIS.

## Subroutine LØADRR

Object  Loader formated input

Options

NØPT8=0  Continue reading input
NØPT8=1  Stop reading input

List of Symbols

See EQUIVALENCE ARRAYS in subroutine listings.

Theory

This method of reading input permits the changing of one or more input variables. The remaining input variables remain the same as the previous case.

## Subroutine MINVRT(A,B,N)

**Object** Invert NxN matrix.

**Options**

None

**List of Symbols**

| | | |
|---|---|---|
| A | = $\bar{\bar{A}}$ | , Augmented $\bar{\bar{A}}$ matrix |
| B | = $\bar{\bar{B}}$ | , Augmented $\bar{\bar{B}}$ matric ($\bar{\bar{A}}^{-1}$) matrix |
| N | | , Number of equations (rows) |
| M | | , Number of columns |

**Theory**

The $\bar{\bar{A}}$ matrix is inverted using the Gauss-Jordan elimination procedure. First the augmented $\underset{\sim}{\bar{\bar{A}}}(N, M)$ is formed including the identity matrix,

$$\underset{\sim}{\bar{\bar{A}}} = (A \; I) \tag{1}$$

Then the following revision formula is used

$$b_{I-1,J-1} = a_{I,J} - a_{1,J}a_{I,1}/a_{1,1} \qquad \left\{ \begin{matrix} 1 < I \leq N \\ 1 < J \leq M \end{matrix} \right\} \tag{2}$$

$$b_{N,J-1} = a_{1,J}/a_{1,1} \qquad 1 < J \leq M \tag{3}$$

Note that the $\bar{\bar{B}}$ matrix has one less column than the $\underset{\sim}{\bar{\bar{A}}}$ matrix. Then the substitution is made

$$a_{IJ} = b_{IJ} \qquad \begin{matrix} 1 \leq T \leq N \\ 1 \leq J \leq M-1 \end{matrix} \tag{4}$$

and repeated until the $\bar{\bar{B}}$ matrix is an NxN or the $\bar{\bar{A}}^{-}$ matrix.

## Subroutine MYTIME

Object    Dummy time trap routine

## Subroutine ØUTPUT

Object

Print title page

Option

None

List of Symbols

None

Theory

This subroutine prints the title page which records all modifications, dates, and references to changes incorporated into the ADD code.

## Subroutine PERFNA

<u>Object</u>   Compute viscous nacelle drag

<u>Options</u>

None

<u>List of Symbols</u>

| | | | | |
|---|---|---|---|---|
| AREAM | = | $A_{max}$ | , | Maximum cross-sectional area |
| CDFR | = | $C_{DF}$ | , | Friction drag coefficient |
| CDPR | = | $C_{DP}$ | , | Pressure drag coefficient |
| DFR | = | $D_F$ | , | Friction drag (lb) |
| QREF | = | $Q_r$ | , | Reference dynamic pressure (psf) |
| RMAX | = | $R_{max}$ | , | Maximum radius of nacelle |
| AVE(9,1) | = | $P_1$ | , | Initial mass flow average density |
| AVE(4,1) | = | $U_1$ | , | Initial mass flow average velocity |
| P | = | P | , | Static pressure |
| P1,P2 | = | $\Pi_1, \Pi_2$ | , | Static pressure $(P/P_r)$ at prescribed stations |
| R | = | R | , | Local radius |
| R1,R2 | = | $R_1, R_2$ | , | Nacelle radius $(r_1/r_r)$ of prescribed stations |
| S | = | S | , | Streamwise coordinates |
| $S_1, S_2$ | = | $S_1, S_2$ | , | Streamwise coordinate at prescribed stations |

<u>Theory</u>

In terms of dimensionless variables used in the analysis, the friction and pressure drag are given by:

$$D_f = 2\pi r_r^2 \rho_r u_r^2 \int_{S_1}^{S_2} R \sum_{ns} \frac{\partial R}{\partial n} ds \qquad (1)$$

$$D_P = 2\pi\, r_r^2\, P_r \left\{ \int_{S_1}^{S_2} R\, \Pi \frac{\partial R}{\partial S}\, ds + \Pi_1 \frac{R_1^2}{2} - \Pi_2 \frac{R_2^2}{2} \right\} \tag{2}$$

The corresponding coefficients are given by

$$C_{DP} = D_P / (A_{MAX} Q_r) \tag{3}$$

$$C_{DF} = D_f / (A_{MAX} Q_r) \tag{4}$$

where

$$A_{MAX} = \pi\, r_r^2\, R_{MAX}^2 \tag{5}$$

$$Q_r = 1/2\, \rho_r\, u_r^2\, \bar{\rho}_1 \bar{u}_1^2 \tag{6}$$

Subroutine PERFN2

Object  Compute inviscid nacelle drag

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| DPR | = | $D_p$ | , Pressure drag |
| P | = | P | , Static Pressure |
| P1,P2 | = | $P_1, P_2$ | , Static pressure $(P/P_r)$ at prescribed stations |
| R1, R2 | = | $R_1$, $R_2$ | , Nacelle radius $(r_1/r_r)$ at prescribed stations. |
| S | = | S | , Streamwise coordinate. |
| $S_1, S_2$ | = | $S_1, S_2$ | , Streamwise coordinate at prescribed station. |

Theory

In terms of the dimensionless variables used in the analysis, the pressure drag is given by;

$$D_P = 2\pi\, r_r^2\, P_r \left\{ \int_{S_1}^{S_2} R\, \Pi \frac{\partial R}{\partial S}\, ds + \Pi_1 \frac{R_1^2}{2} - \Pi_2 \frac{R_2^2}{2} \right\} . \qquad (1)$$

## Subroutine PØIS (RESM,ITER)

### Object

Solve Poisson equation

### Option

| | | |
|---|---|---|
| IDBGP | = 0 | No debug printout |
| | = 1 | Printout residuals |
| | = 2 | Print solution |

### List of Symbols

| | | | |
|---|---|---|---|
| P(K,J) | = | $\psi$ | , Stream function (dimensionless) |
| F(K,J) | = | | , Coefficient (1/$\underline{P}$G) (dimensionless) |
| PSI(K) | = | $\tilde{\psi}$ | , Iterative guess for J |
| ITER | = | $\nu$ | , Iteration counter |
| RLX | | | , Relaxation factor |
| RESMAX | = | $\varepsilon_{MAX}$ | , Maximum residual accepted |
| RESDM | = | $\varepsilon_M$ | , Maximum residual/J station |
| RESM | = | $\varepsilon$ | , Maximum residual/sweep |

### Theory

The solution algorithm is described in Reference 1.

### References


1. Anderson, O. L. and D. E. Edwards: Extension to an Analysis of Turbulent Swirling Compressible Flow in Axisymmetric Ducts, NASA Contract NAS3-21853, 1981, UTRC Report R81-914720.

## Subroutine PØISCF

Object

(1) Set of coefficients of $\nabla^2 \psi = 0$
(2) Set boundary conditions on $\psi$
(2) Set initial guess for $\psi$

Options

| | | |
|---|---|---|
| IDBG17 | = 0 | Compressible Flow |
| | = 1 | Incompressible Flow |
| IDBGT | = 0 | No debug test case |
| | = 1 | Debug test case |
| IDBGP | = 0 | No debug test printout |
| | = 1 | Debug printout |

Variables

| | | | |
|---|---|---|---|
| Q(I,K) | | | , Coordinate functions |
| FIV(I,L,K) | | | , Dependent variables for inviscid flow |
| P(K) | = | $\psi_K^J$ | , Stream function at station J |
| A(K) | = | $GP/V/(d\eta/dn)$ | , Coefficient for $\partial\psi/\partial\eta$ |
| F(K) | = | $1/G/P$ | , Coefficient of $\nabla^2\psi$ |
| G(K) | = | $V/G/P$ | , Coefficient for velocity calculation |
| R(K) | = | $P$ | , Density ratio $(\rho/\rho_r)$ |
| T(K) | = | $\Theta$ | , Temperature ratio $(T/T_r)$ |
| V(K) | = | $V$ | , Metric coefficient dimensionless |
| GAP | = | $G$ | , Gap $(g/r_r)$ |
| VMET | = | $V$ | , Metric coefficient (dimensionless) |
| RHØ | = | $P$ | , Density ratio $(\rho/\rho_r)$ |
| TEM | = | $\Theta$ | , Temperature ratio $(T/T_r)$ |
| USO | = | $U_{so}$ | , Upstream constant velocity $(u_o/u_r)$ |

| | | |
|---|---|---|
| USINF | $U_{s\infty}$ | ,Free stream axial velocity ($u_{s\infty}/u_r$) |
| UPINF | $U_{\phi\infty}$ | ,Free stream tangential velocity $u_{\phi\infty}/u_r$ |
| PSIKL | $\psi_\infty$ | ,Free stream stream function (dimensionless) |
| TEMINF | $\theta_\infty$ | ,Free stream static temperature ratio ($T/T_r$) |
| RHOINF | $P_\infty$ | ,Free stream density ratio ($\rho/\rho_r$) |
| AMINF | $M_\infty$ | ,Free stream Mach number |
| PTINF | $\Pi_\infty$ | ,Free stream total pressure ratio ($P_0/P_r$) |
| BLK | | ,See COMMON/SPCGD/ |

Theory

This subroutine does the following steps

(1) Reads coordinate Q file and solution FIV file
(2) Interpolates the solution to the ($\eta$,S) grid
(3) Calculates the coefficient $F = 1/PG$
(4) Calculates coefficients BLK for streamline curvature calculation
(5) Sets boundary condition on $\Psi$
(6) Calculates initial guess for $\Psi$
(7) Stores F, BLK, P on disk files

The initial guess is given by the inviscid solution obtained from CALINV. The boundary conditions are given by:

$$\psi(0,s) = 0 \tag{1}$$

$$\psi(1,s) = \psi_\infty \tag{2}$$

$$\psi(\eta,0) = U_{so} \int_0^{\eta} \left(\frac{GP}{V} \Big/ \frac{d\eta}{dn}\right)_{s=0} d\eta \tag{3}$$

$$\psi(\eta,s_L) = U_{so} \int_0^{\eta} \left(\frac{GP}{V} \Big/ \frac{d\eta}{dn}\right)_{s=s_L} d\eta \tag{4}$$

## Subroutine PØISØN

### Object

Calculate axisymmetric streamline curvature

### Options

| | | | |
|---|---|---|---|
| IØPT7 | = | 0 | No curvature corrections |
| | = | 1 | Curvature correction |
| IDBG15 | = | 0 | Use input KL streamlines |
| | > | 0 | Use IDBG15 streamlines |

### List of Symbols

| | |
|---|---|
| IRHØ | ,Density iteration counter |
| ITERL | ,Maximum number of iterations |
| KHØLD | ,No. ADD code streamlines |
| KL | ,No. SCURVA streamlines |
| RESMAX | ,Maximum residual for convergence |

### Theory

This subroutine is a calling subroutine for subroutines INTFRE, PØISCF, PØIS, and SCURVA.

## Subroutine QINTER

Object

Interpolate curvature from PØIS mesh to SØLVI mesh

Options

None

List of Symbols

| | |
|---|---|
| Q(J,K) | Coordinate functions |

Theory

After the curvature and flow angle has been calculated from the potential flow solution, this subroutine interpolates to obtain values at the numerical grid points which will be used in the SØLVI calculation.

## Subroutine READPF(J,JJ)

### Object

Read P and F files in NIST word blocks

### Option

None

### List of Symbols

| | | |
|---|---|---|
| J | J | ,Record number |
| JJ | JJ | ,Record number in block N |
| N | N | ,Block number |
| F | F | ,Coefficients of $\nabla^2\psi = 0$ |
| P | $\psi$ | ,Stream function (dimensionless) |
| NST | = 25 | ,Number of records per block |
| NBK | | ,Number of words to move pointer |
| NIST | | ,Number of words per block |
| NFDRM | = 23 | ,Coefficient file number F array |
| NL | | ,Last block number |
| NBIST | | ,Number of words for two records |
| NMOVE | | ,Number of words to move pointer |

### Theory

The entire F and P arrays cannot be kept in core at the same time so that the I/O is arranged to keep fixed blocks in core (Fig. 1). Let (J,K) be a point on the computational mesh and (JJ,KK) the corresponding point in core. Let each record be the Jth line with the number of words in the record given by

$$K = 1,IST$$

If there are NST records per block, then these are NIST words per block,

$$NIST = NST \times IST$$

Theory (Cont'd)

The solution algorithm requires overlapping blocks as shown on Fig. 1. Hence we have the block number

$$N = (J-2)/(NST-2) + 1$$

and the JJ point in core is given by

$$JJ + J-(N-1) \times (NST-2)$$

This subroutine is coded so that a new block is ready only when N = NL.

## Subroutine READPG(J,JJ)

### Object

Read variable for curvature calculation

### Options

None

### List of Symbols

| | | |
|---|---|---|
| J | = J | ,Record number |
| JJ | = JJ | ,Record number in block N |
| N | | ,Block number |
| G | | ,Streamline coordinate data (see COMMON/SPCFD/) |
| P | | ,Stream function |
| NST | = 25 | ,Number of records per block |
| NBK | | ,Number of words to move pointer |
| NIST | | ,Number of words per P block |
| NGDRM | = 25 | ,Unit number of G array |
| NPDRM | = 24 | ,Unit number for P array |
| NL | | ,Last P block number |
| NBIST | | ,No. words for 2 P records |
| NGIST | | ,No. words for 2 G records |
| NGL | | ,Last G record number |

### Theory

This subroutine reads the P file according to Subroutine READPF but reads only the Jth G record which is kept in core.

Function RØBRTS(C,ETA,LØP)

Object

Compute distorted mesh using Roberts' transformation

Options

LØP = 0 Wall - wall boundary
= 1 Wall-free stream boundary
=-1 Free stream-wall boundary

List of Symbols

| | | | |
|---|---|---|---|
| C | = | C | ,Distortion parameter |
| ETA | = | $\eta$ | ,Input variable (uniform mesh) |
| LØP | = | | ,Option |

Output Variable

RØBRTS = n ,Output variable

Theory

The Roberts' transformation for a distorted mesh on both sides is given by

$$n' = \frac{(c+1/2)\exp\left[2\ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta'-1/2\right)\right]-(c-1/2}{1+\exp\left[2\ln\left(\frac{c+1/2}{c-1/2}\right)\left(\eta'-1/2\right)\right]} \tag{1}$$

where

$$0 \le \eta' \le 1.0 \qquad 0 \le n' \le 1.0 \tag{2}$$

For the different options we have

$$\left.\begin{matrix} \eta' = \eta \\ n = n' \end{matrix}\right\} L\emptyset P = 0 \tag{3}$$

$$\left.\begin{matrix} \eta' = \eta/2 \\ n = 2n' \end{matrix}\right\} L\emptyset P = 1 \tag{4}$$

$$\left.\begin{matrix} \eta' = (1+\eta)/2 \\ n = 2n' - 1 \end{matrix}\right\} L\emptyset P = -1 \tag{5}$$

## Subroutine RØUND

Object  Round corners on straight wall ducts.

List of Symbols

| | |
|---|---|
| XM | , Axial location |
| IWALL | , Indicates Hub or Tip Wall |
| DX | , Stepsize in x direction |

Theory

In subroutine GDUCT, if the option IØPT3 = 8 is used then a straight wall is constructed between initial data points. Thus in order to remove discontinuity between wall segments this subroutine is used to round or smooth out the discrete representations of the wall in order for it to appear smooth.

## Subroutine SLETE(KSSLE,KSSTE)

Object  Find blade control surfaces.

Options

None.

List of Symbols

| | |
|---|---|
| KSSLE,KSSTE | , Leading edge and trailing edge index |
| SLE,STE | , Leading and trailing edge coordinates (dimensionless) |
| ZLEH,ZLET | , Axial distance hub leading and trailing edge (dimensionless) |
| ZTEH,ZTET | , Axial distance tip leading and trailing edge (dimensionless) |

Theory

The intersection of the leading and trailing edge of the blade with the hub and tip casing are obtained from Subroutine GBLADE. Then the coordinates of the hub and tip boundaries are searched until the proper value of streamwise coordinates for the leading edge and trailing edge of the blade are found. The coordinate index KSSLE is located just upstream of the blade and the coordinate KSSTE is located just downstream of the blade.

## Subroutine SCURVA (IDBU,KHØLD)

### Object

Calculate curvature from potential flow solution

### Options

IDBU = 0 Update density
> 0 Print SCURVA solution, update curvature

### Variables

| | | |
|---|---|---|
| KHØLD | | ,No. ADD code streamlines |
| KL | | ,No. SCURVA streamlines |
| Q(J,K) | | ,Coordinate functions |
| P(K) | $\psi_k^J$ | ,Stream function a station J (dimensionless) |
| G(K) | G | ,Coefficient for velocity calculation |
| R(K) | P | ,Density Ratio $(P/P_r)$ (dimensionless) |
| US | $U_s$ | ,Streamwise velocity (dimensionless) |
| UN | $U_n$ | ,Normal velocity (dimensionless) |
| U | U | ,Total velocity (dimensionless) |
| COSTH | $\cos^2(\theta)$ | ,$(\text{Cosine})^2$ of flow angle $\theta$ |
| CURV | $\frac{\partial V}{\partial n}$ | ,Curvature of streamline (dimensionless) |

### Theory

Once the potential flow solution has been obtained from subroutine PØIS, this subroutine will calculate the flow angle and streamline curvature according to Ref. (1).

### References

1. Anderson, O.L. and D. E. Edwards, Extension to an Analysis of Turbulent Swirling Compressible Flow in Asixymmetric Ducts, NASA Contract No. NAS3-21851, 1981, UTRC Report R81-914720.

## Subroutine SMØØTH (X,J,JX,XB,YB,JXB,JXK)

Object Least squares spline fit smoothing for geometry

Options

None

List of Symbols

| | | |
|---|---|---|
| JX | | , Number of input points |
| JXB | | , Number of output points |
| JXK | | , Number of spline knots |
| X(J) | $= X_J$ | , Input points abscissa |
| Y(J) | $= Y_J$ | , Input points ordinate |
| XB(J) | $= \bar{X}_J$ | , Output points abscissa |
| YB(J) | $= \bar{Y}_J$ | , Output points ordinate |
| YPP(J) | $= Y_J$ | , Second derivative of Y(X) |
| CK(I,J) | $= C(I,J)$ | |
| YK(I) | $= Y_K$ | , Spline coefficients |
| A(I),B(I) | $= A_I, B_I$ | , Constants of Integration |

Theory

This subroutine computes the second derivative of the input vector Y(X). With the use of the standard math package ISML routines, (reference 9) it then fits a least square spline to the second derivative with JXK movable knots. The spline equations are then integrated analytically to obtain the output solution vector $\bar{Y}(\bar{X})$ at JXB points. Subroutine SMØØTH uses ISML routines ICSFKU, ICSFKV, UERTST.

Subroutine SØLVI

Object Integrate equations of motion for viscous flow.

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| AA(I,J) | = | $a_{IJ}$ | , Element of $\bar{\bar{A}}$ matrix |
| AB(I,J) | = | $b_{IJ}$ | , Element of $\bar{\bar{B}}$ matrix |
| AC(I,J) | = | $c_{IJ}$ | , Element of $\bar{C}$ matrix |
| AD(I,J) | = | $d_{IJ}$ | , Element of $\bar{\bar{D}}$ matrix |
| ADI(I,J) | = | $\left(d_{IJ}{}^{-1}\right)_K$ | , Element of $\bar{\bar{D}}^{-1}$ matrix |
| AE(I,J,K) | = | $e_{IJ}$ | , Element of $\bar{\bar{E}}^k$ matrix |
| AQ(I) | = | $q_I$ | , Element of $\bar{\bar{Q}}$ matrix |
| AZ(I,K) | = | $z_I^K$ | , Element of $\bar{\bar{Z}}^k$ matrix |
| CFPH | = | $C_{f\phi H}$ | , Stress coefficient hub $(2\varepsilon_{n\phi}/(\bar{P}_1\bar{U}_1{}^2))$ |
| CFPT | = | $C_{f\phi T}$ | , Stress coefficient tip $(-2\varepsilon_{n\phi}/(\bar{P}_1\bar{U}_1{}^2))$ |
| CFST | = | $C_{fSH}$ | , Stress coefficient hub $(2\varepsilon_{ns}/(\bar{P}_1\bar{U}_1{}^2))$ |
| CFST | = | $C_{fST}$ | , Stress coefficient tip $(-2\varepsilon_{ns}/(\bar{P}_1\bar{U}_1{}^2))$ |
| DAYE | = | $1/4(\bar{\rho}\ U_1{}^2)$ | , Mean inlet dynamic pressure (dimensionless) |
| EENTP | = | E(I) | , Truncation error ($\pi$) |
| ENREF | = | $\bar{I}_1$ | , Mean inlet entropy |
| EPRES | = | $E(\pi)$ | , Truncation error ($\pi$) |
| ERØTH | = | $\varepsilon(P\Theta)$ | , Truncation error ($P\Theta$) |
| ERØUS | = | $\varepsilon(PU_s)$ | , Truncation error ($PU_s$) |

| | | | |
|---|---|---|---|
| EUPUP | = | $E(U_{\emptyset}^{2})$ | , Truncation error $(U_{\emptyset}^{2})$ |
| EUSUS | = | $E(U_{s}^{2})$ | , Truncation error $(U_{s}^{2})$ |
| PIREF | = | $\bar{\Pi}1$ | , Mean inlet reference pressure (dimensionless) |
| PIO | = | $\Pi_{o}$ | , Total pressure (dimensionless) |
| PRCEF | = | $C_{P}$ | , Local pressure coefficient (dimensionless) |
| PSIH1, PSIH2 | = | $\psi_{H}^{J}, \psi_{H}^{J-1}$ | , Wall stream function (hub) (dimensionless) |
| PSIT1, PSIT2 | = | $\psi_{T}^{J}, \psi_{T}^{J-1}$ | , Wall stream function (tip) (dimensionless) |
| QAVE | = | $\bar{P}\bar{U}_{S}(\bar{\theta}_{O}-\bar{\theta})$ | , Inlet energy flux (dimensionless) |
| QWALH | = | $P_{H}U_{H}^{*3}$ | , Energy flux (hub) (dimensionless) |
| QWALT | = | $P_{T}U_{T}^{*3}$ | , Energy flux (tip) (dimensionless) |
| QPLUS | = | $Q/(PU^{*3})$ | , Universal heat flux (dimensionless) |
| SIG | = | $\varepsilon$ | , Stress (dimensionless) |
| SIGWH | = | $\varepsilon_{WH}$ | , Wall stress (hub) (dimensionless) |
| SIGWT | = | $\varepsilon_{WT}$ | , Wall stress (tip) (dimensionless) |
| STAH | = | $S_{tH}$ | , Stanton number (hub) $Q_{H}/[\bar{P}\bar{U}_{s}(\bar{\theta}_{o}-\theta)]$ |
| STAT | = | $S_{tT}$ | , Stanton number (tip) $Q_{T}/[\bar{P}\bar{U}_{s}(\bar{\theta}_{o}-\theta)]$ |
| THETAO | = | $\theta_{o}$ | , Total temperature (dimensionless) |
| TPLUS | = | $\tau^{+}$ | , Universal stress (dimensionless) |
| TWH,TWT | = | $\theta_{H}, \theta_{T}$ | , Wall temperature (hub, tip) (dimensionless) |
| U | = | $U$ | , Magnitude of velocity (dimensionless) |
| UPLUS | = | $U^{+}$ | , Universal velocity (dimensionless) |
| USH,UST | = | $U_{H}^{*}, U_{T}^{*}$ | , Friction velocity (hub, tip) (dimensionless) |

| | | |
|---|---|---|
| XMACH | $= M$ | , Mach number (dimensionless) |
| YPLUS | $= Y^{+}$ | , Universal distance (dimensionless) |
| Z | $= Z$ | , Axial distance (dimensionless) |
| ZZ | $= Z_s$ | , Axial distance to next slot (dimensionless) |

Theory

The equations of motion are solved using the method derived in reference 6. A flow diagram is shown in Fig. 24.

## Subroutine STRESI

Object  Compute initial stress distribution

Options

LØP=1  Store inlet flow stress
LØP≠1  Do not store inlet flow stress

List of Symbols

See CØMMØN block variables in subroutine listings.

Theory

The initial stress and heat flux distribution is computed from

$$\Sigma_{ns} = \left(\frac{\mu_T}{\mu_r}\right) \frac{E_{ns}}{N_R} \tag{1}$$

$$\Sigma_{n\phi} = \left(\frac{\mu_E}{\mu_r}\right) \frac{E_{n\phi}}{N_R} \tag{2}$$

$$Q = -\frac{1}{N_R P_{RE}} \left(\frac{\mu_E}{\mu_r}\right) V \frac{\partial \Theta}{\partial n} \tag{3}$$

## Subroutine STRT

Object    Find inlet flow location

Option

None

List of Symbols

| | |
|---|---|
| ZINLET | , Axial inlet flow location |
| SINLET | , Streamwise inlet flow location |
| INLET | , Counter |

Theory

Once the axial location of the inlet flow is determined the streamwise location may be found since the axial location at each point in the coordinate system is paired with its streamwise coordinate.

## Subroutine TPRINT

Object    Calls CPU time.

## Subroutine TURB

Object    Compute turbulent viscosity

Options

NØPT=0  Initial turbulence model
NØPT=1  Subsequent turbulence model

List of Symbols

| | | |
|---|---|---|
| AMUE | $= \mu_T/\mu_r$ | , Turbulent viscosity (dimensionless) |
| AMUER(K) | $= (\mu_{T_\infty}/\mu_r)$ | , Freestream turbulent viscosity (dimensionless) |
| AMUM | $= \mu_\infty/\mu_r$ | , Freestream molecular viscosity (dimensionless) |
| AMUW | $= \mu_w/\mu_r$ | , Wall value of molecular viscosity (dimensionless) |
| AMUWK | $= (\mu/\mu_r)_{K+\frac{1}{2}}$ | , Molecular viscosity (dimensionless) |
| AMUO | $= (\mu_{T_\infty}/\mu_\infty)$ | , Maximum freestream viscosity (dimensionless) |
| DELO | $= \Delta_\infty$ | , Displacement thickness (dimensionless) |
| DU | $= \Delta U$ | , Velocity finite-difference (dimensionless) |
| DUDZ | $= dU/dZ$ | , Velocity derivative (dimensionless) |
| E | $= E$ | , Rate of strain (dimensionless) |
| EM | $= E_\infty$ | , Strain freestream (dimensionless) |
| EMH, EMT | $= E_{\infty H}, E_{\infty T}$ | , Strain hub, tip, edge of inner layer (dimensionless) |
| ENP | $= E_{n\phi}$ | , Swirl rate of strain (dimensionless) |
| ENS | $= E_{ns}$ | , Streamwise rate of strain (dimensionless) |
| EW | $= E_w$ | , Wall rate of strain (dimensionless) |
| PHI | $= \phi$ | , Turbulence model function (dimensionless) |
| RHØM | $= \rho_\infty$ | , Density freestream (dimensionless) |

| | | | |
|---|---|---|---|
| SIGWH | = $\Sigma_{wh}$ | , | Wall stress (hub) (dimensionless) |
| SIGWK | = $\Sigma_{wk}$ | , | Wall stress (inner layer) (dimensionless) |
| SIGWT | = $\Sigma_{wt}$ | , | Wall stress (tip) (dimensionless) |
| TPLUS1, TPLUS2 | = $T_1^+, T_2^+$ | , | Universal wall stress (dimensionless) |
| UK(K) | = $U_K$ | , | Magnitude of velocity (dimensionless) |
| UM | = $U_\infty$ | , | Freestream velocity (dimensionless) |
| USTARH, USTART | = $U_H^*, U_T^*$ | , | Friction velocity (hub, tip) (dimensionless) |
| Y | = Y | , | Distance across duct (dimensionless) |
| YK | = $Y_{k+\frac{1}{2}}$ | , | Distance across duct (dimensionless) |
| YMH, YMT | = $Y_H, Y_T$ | , | Distance to inner layer (hub, tip) (dimensionless) |
| YPLUS1, YPLUS2 | = $Y_1^+, Y_2^+$ | , | Universal distance (dimensionless) |

Theory

The turbulence model is described in reference (1) and the resulting equations are described below. Let the eddy viscosity be described by a continuous function

$$\frac{\mu_E}{\mu_r} = \phi E \qquad (1)$$

where

$$E = \sqrt{E_{ns}^2 + E_{n\phi}^2} \qquad (2)$$

and

$$\phi = \rho_w N_R (\kappa y)^2 \left\{ 1 - \exp\left[\frac{-y + \sqrt{\tau^+}}{A^+}\right]^2 \right\} \text{ (inner layer)} \qquad (3)$$

$$\phi = \frac{X N_R \rho_\infty U_\infty \Delta^*}{E_M} \quad \text{(outer layer)} \tag{4}$$

where $\tilde{y}$ is the distance from the wall

$$\tilde{y} = |y - y_w| \tag{5}$$

A matching point for the inner layer and outer layer exists for each wall denoted $Y_H$ and $Y_T$ and with a corresponding strain $E_H$ and $E_T$. Then for the outer layer

$$E_M = E_H + \frac{E_T - E_H}{y_T - y_H} (y - y_H) \tag{6}$$

The turbulent viscosity and thermal conductivity is given by

$$\frac{\mu_T}{\mu_r} = \frac{\mu}{\mu_r} + \frac{\mu_E}{\mu_r} \tag{7}$$

$$\frac{1}{P_{RE}} \frac{\mu_r}{\mu_r} = \frac{1}{P_{rL}} \frac{\mu}{\mu_r} + \frac{1}{P_{RT}} \frac{\mu_E}{\mu_r} \tag{8}$$

The turbulent flow properties can be calculated at station J-1 because the flow field is known. For station J, it is noted that the turbulent viscosity is a strong function of stress, thus from equation (1),

$$\left(\frac{\mu_E}{\mu_r}\right)^2 = N_R \phi \Sigma \tag{9}$$

where

$$\Sigma = \sqrt{\Sigma_{ns}^2 + \Sigma_{n\phi}^2} \tag{10}$$

Hence,

$$\left(\frac{\mu_T}{\mu_r}\right)^J = \left(\frac{\mu_T}{\mu_r}\right)^{J-1} + \left[\frac{\partial}{\partial \Sigma}\left(\frac{\mu_E}{\mu_r}\right)\right]^{J-1} \left(\Sigma^J - \Sigma^{J-1}\right) \tag{11}$$

$$\left(\frac{1}{P_{RE}} \frac{\mu_r}{\mu_r}\right)^J = \left(\frac{1}{P_{RE}} \frac{\mu_r}{\mu_r}\right)^{J-1} + \left[\frac{\partial}{\partial \Sigma}\left(\frac{\mu_E}{\mu_r}\right)\right]^{J-1} \left(\Sigma^J - \Sigma^{J-1}\right) \tag{12}$$

and

$$\left[\frac{\partial}{\partial \Sigma}\left(\frac{\mu_E}{\mu_r}\right)\right]^{J-1} = \frac{N_R}{2E^{J-1}} \tag{13}$$

Finally, it is noted that at the initial station $\tau^+(Y^+)$ in equation 3 is not known, therefore, $\tau^+ = 1$ is assumed.

## Function UBLAS

Object Calculate velocity ratio according to the Blasius solution for the initial flow.

Options

None

Theory

The velocity ratio is determined by interpolations of data block containing Blasius solution to the flow past an axisymmetric shape (reference 10).

Function UCØLES (Argument List)

Object Find friction velocity for the initial profile from Coles law

Options

None

List of Symbols

| | | |
|---|---|---|
| AK | $= k$ | , Von Karman constant (dimensionless) |
| ANUW | $= \nu_w$ | , Kinematic viscosity ($ft^2$/sec) |
| DELT | $= \delta$ | , Boundary layer thickness (ft) |
| DELTS | $= \delta^*$ | , Displacement thickness (ft) |
| DERR | $= dE/dU^*$ | , Slope of error function (dimensionless) |
| ERR | $= E$ | , Error function (dimensionless) |
| ERRM | $= \varepsilon$ | , Convergence criteria (dimensionless) |
| ITER | $= \mu$ | , Iterate |
| ITERL | $= \mu$ | , Maximum number of iterations |
| UINF | $= U_\infty$ | , Freestream velocity (ft/sec) |
| US | $= (U^*)^\nu$ | , Guess for friction velocity (ft/sec) |
| US1 | $= (U^*)^1$ | , Initial guess for $U^*$ (ft/sec) |

Theory

The friction velocity is obtained from Coles law using Newton's method

$$E^\mu = \frac{U_\infty}{(U^*)^\mu} - \left\{ \frac{1}{\kappa} \ln \left[ \frac{\delta (U^*)^\mu}{\nu_w} \right] + \frac{2.2}{\mu} + 2 \left[ \frac{\delta^*}{\delta} \frac{U_\infty}{(U^*)^\mu} - 1 \right] \right\} \quad (1)$$

$$\left( \frac{dE}{dU^*} \right)^\mu = \left( \frac{2\delta^*}{\delta} - 1 \right) \frac{U_\infty}{(U^{*2})^\mu} - \frac{1}{\kappa} \frac{\nu_w}{\delta^* (U^*)^\mu} \quad (2)$$

$$(U^*)^{\mu+1} = (U^*)^{\mu} - E^{\mu}\Big/\left(\frac{dE}{dU^*}\right)^{\mu} \tag{3}$$

Convergence occurs when

$$|E^{\mu}| < \varepsilon \tag{4}$$

## Subroutine WAKCØR

Object  Compute nacelle wake corrections.

Options

None

List of Symbols

| | | | |
|---|---|---|---|
| AM1,AM2 | = | $M_{k-1}$, $M_k$ | , Inviscid flow Mach number |
| DRL | = | $\Delta R_L$ | , Radial wake correction |
| DZL | = | $\Delta Z_L$ | , Axial wake correction |
| ETA | = | $\eta$ | , Normal coordinate |
| G(1,J,L) | = | $\psi_L$ | , Wake distance (radians) |
| G(2,J,L) | = | $\Delta\psi$ | , Tangential wake correction |
| G(3,J,L) | = | $\partial\psi/\partial s$ | , Partial derivative |
| G(4,J,L) | = | $\partial\Delta\psi/\partial s$ | , Partial derivative |
| G(5,J,L) | = | $\Delta R$ | , Radial wake correction |
| G(6,J,L) | = | $\Delta Z$ | , Axial wake correction |
| RL | = | $R_L$ | , Radial location of lifting line streamline |
| SL | = | $S_L$ | , S coordinate of lifting line streamline |
| S2,S1 | = | $S_J, S_{J-1}$ | , S coordinate of mesh |
| TØT1,TØT2 | = | $(T_o/T)_{K-1}, (T_o/T)_K$ | , Total to static temperature ratio |
| T1, T2 | = | $T_{K-1}$, $T_K$ | , Static temperature |
| U1, U2 | = | $U_{K-1}$, $U_K$ | , Inviscid flow velocity |
| US1, US2 | = | $U_{S_{K-1}}$, $U_{S_K}$ | , Inviscid flow streamwise velocity |
| UP1, UP2 | = | $U_{\phi_{K-1}}$, $U_{\phi_K}$ | , Inviscid flow tangential velocity |
| VL | = | $V_L$ | , Metric scale coefficient of $L^{th}$ streamline |

| | |
|---|---|
| ZL | , Axial distance $L^{th}$ streamline |
| J | , Index of S coordinate |
| K | , Index of N coordinate |
| L | , Index of $L^{th}$ streamline |

Theory

To obtain the corrections to the wake geometry due to the nacelle's presence in the flow field, this subroutine integrates the following equations. (formulted in reference 1).

$$\tilde{\Psi}(S_J, R_L) = \Omega \int_{S_L}^{S_J} \frac{ds}{U_S V} \tag{1}$$

$$\Delta\tilde{\Psi}(S_J, R_L) = \int_{S_L}^{S_J} \frac{U\phi}{RU_S} \frac{ds}{V} \tag{2}$$

using the trapezoid rule along the streamlines passing through the point $(R_L, Z_L)$ or $(S_L, n_L)$. The remaining wake corrections are given by

$$\Delta R_L = R_L(S_J) - R_L \tag{3}$$

$$\Delta Z_L = Z_L(S_J) - Z_L(S_L) - \frac{U_\infty}{\Omega}\Psi \tag{4}$$

Labeled Common Blocks Used in The Nacelle Portion

Included herein is an alphabetical list of the labeled common blocks used in the nacelle portion of the analysis and a description of each variable used in them.

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| ACØNS (Blade Data - Dimensionalized) | CØNSTI (1, L) = $R_{CL}$ | Radius of propeller lifting line |
| | CØNSTI (2, L) = $\alpha_S$ | Stagger angle |
| | CØNSTI (3, L) = B | Chord |
| | CØNSTI (4, L) = $t/_B$ | Thickness |
| | CØNSTI (5, L) | Not used |
| | CØNSTI (6, L) = $Z_{CL}$ | Axial location of propeller lifting line |

## Subroutine WBLEED

### Object

Calculate perforated wall bleed

### Options

| | | |
|---|---|---|
| IØPT18 | = 0 | No wall bleed |
| | = 1 | Tip wall bleed |
| | = 2 | Hub wall bleed |
| | = 3 | Tip/hub wall bleed |
| PCHEK | > 1.0 | Flow enters tunnel |
| | < 1.0 | Flow leaves tunnel |

### Input Variables

| | | |
|---|---|---|
| AHAS | = $A_h/A_s$ | Ratio of hole area to surface area |
| CDISH | = C | Discharge coefficient |
| PTP | = $P_{TP}$ | Plenum total pressure |
| TTP | = $T_T$ | Plenum total temperature |

### Internal Variables

| | | |
|---|---|---|
| AMTU | = $M_{TU}$ | Tunnel Mach number |
| GAMMA | = $\gamma$ | Ratio of specific heats |
| GASR | = R | Gas constant |
| PS | = P | Static pressure (psfa) |
| PT | = $P_T$ | Total pressure (psfa) |
| PSTU | = $P_{TU}$ | Tunnel static pressure (psfa) |
| PTTU | = $P_{TTU}$ | Tunnel total pressure (psfa) |
| TSTU | = $T_{TU}$ | Tunnel static temperature (deg R) |
| TTTU | = $T_{TTU}$ | Tunnel total temperature (deg R) |
| RHØR | = $\rho_r$ | Reference density (slug/ft$^3$) |
| USR | = $u_r$ | Reference velocity (ft/sec) |
| PRESR | = $P_r$ | Reference pressure (psfa) |

Internal Variables (Cont'd)

| | | |
|---|---|---|
| TEMPR | $= T_r$ | Reference temperature (deg R) |
| SGN | $\pm 1$ | Sign convention |

Output Variables

| | | |
|---|---|---|
| RH(9,J) | $= (\rho U_n)_H$ | Mass bleed hub wall (slugs/ft$^2$/sec) |
| RT(9,J) | $= (\rho U_n)_T$ | Mass bleed tip wall (slugs/ft$^2$/sec) |

Theory

If one treats a single hole in a perforated wall as an orifice, then the mass flow can be derived in terms of the plenum stagnation conditions and the local static pressure inside the tunnel Holman (Ref. 1). Then an expression for the mass flow added to the tunnel flow is given by

$$(\rho U_n)_w = C \frac{A_h}{A_s} \frac{\gamma P_T}{\sqrt{\gamma \Re T_T}} \left(\frac{P_T}{P}\right)^{-\frac{1+\gamma}{2\gamma}} \left\{\frac{2}{\gamma-1}\left[\left(\frac{P_T}{P}\right)^{\frac{\gamma-1}{\gamma}} -1\right]\right\}^{1/2} \tag{1}$$

where $P_T$ and $T_T$ are the plenum conditions, P is the local tunnel static pressure, $A_h/A_s$ is the ratio of the hole area to surface area, and C the effective discharge coefficient which is a property of the perforated wall. If the tunnel static pressure is greater than the plenum total pressure, the mass flow bleed is out of the tunnel. Under these conditions, $P_T$ and $T_T$ are taken from the wind tunnel conditions, and P is the plenum pressure which is assumed known.

The mass flow bleed is related to the stream function by

$$-\frac{\partial \Psi}{\partial s} = \frac{G}{V} \frac{(\rho u_n)_w}{\rho_r u_r} \tag{2}$$

Equations (1) and (2) provide the boundary condition for a perforated wall relating two dependent variables $\psi$ and P in terms of the characteristics of the perforated wall and the plenum conditions.

The program checks the options according to the table below.

| | | O.D. Wall | I.D. Wall |
|---|---|---|---|
| $PCHEK = P_{TP}/P_{STU} > 1.0$ set | $P_T = P_{TP}$ | | |
| | $P = P_{STU}$ | SGN = -1.0 | +1.0 |
| | $T_T = T_{TP}$ | | |
| $PCHEK = P_{TP}/P_{STU} < 1.0$ set | $P_T = P_{STU}$ | | |
| | $P = P_{TP}$ | SGN = 1.0 | -1.0 |
| | $T_T = T_{STU}$ | | |

Reference

1. Holman, J. P.: Experimental Methods for Engineers. McGraw-Hill Book Co., New York. 1966.

## Subroutine WRITPF(JJ)

### Object

Store updated potential flow solution.

### Options

None

### List of Symbols

| | |
|---|---|
| JJ | ,JJth station in core |
| NST | ,No. records per block |
| NIST | ,No. words per block |
| NPDRM = 24 | ,Unit number |
| P | ,Stream function |

### Theory

The stream function array P(JJ,KK) is arranged in core as described in subroutine READPF, Fig. 1. When an iterative sweep of one block is complete, the new updated solution is written on a disk file. This occurs when JJ = NST-1.

## Function XH(J)

**Object** Calculate wall length on ID wall

**Variables**

| | | |
|---|---|---|
| J | | Wall point no. |
| XH | $\Delta X_H$ | Wall length |

**Theory**

$$\Delta X_H = ((R_{HJ} - R_{HJ-1})^2 + \Delta Z^2)^{1/2}$$

## Function XT(J)

**Object** Calculate wall length on OD wall

**Variables**

| | | |
|---|---|---|
| J | | Wall point no. |
| XT | $\Delta X_T$ | Wall length |

**Theory**

$$\Delta X_T = ((R_{TJ} - R_{TJ-1})^2 + (Z_{TJ} - Z_{TJ-1})^2)^{1/2}$$

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| ACØNS (Blade Data - Dimensional) | CØNSTI (7, L) | Not used |
| | ØMEGZI = Ω | Propeller rotational velocity |
| | NUM | Number of blade rows |
| | L = 1, 2 | |
| ACØNX (Blade Data - Nondimensional) | CØNST (1, L) | Radius of propeller lifting line (dimensionless) |
| | CØNST (2, L) | Stagger angle (dimensionless) |
| | CØNST (3, L) | Chord (dimensionless) |
| | CØNST (4, L) | Thickness |
| | CØNST (5, L) | Not used |
| | CØNST (6, L) | Axial location of lifting line (dimensionless) |
| | CØNST (7, L) | Not used |
| | CØNST (8, L) | Normal location of lifting line |
| | CØNST (9, L) | Streamwise location of lifting line |
| | L = 1,2 | |
| | ØMEGZ | Rotational velocity (dimensionless) |
| | NUMX | Number of propellers |
| ADPS (Coordinate for Slot Calculations) | DPSI(K) | Radial coordinate (dimensionless) |
| | K = 1, KL | |
| AINV (Store Inviscid Flow Variables) | CINP (1, K) | Total pressure inviscid flow |
| | CINP (2, K) | Static pressure inviscid flow |
| | CINP (3, K) | Swirl angle |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | CINP (4, K) | Total temperature inviscid flow |
| | K = 1, KL | |
| AKK (Complex Coordinate) | M1 | Flags for DEBUG printout |
| | M2 | See Subroutine FCPLX |
| AMATRX (Matrix Inversion) | AD(I,J) = $d_{IJ}$ | Element of D matrix |
| | ADI(I,J) = $\tilde{d}_{IJ}$ | Element of $D^{-1}$ matrix |
| APLØT (Store Variables for Plotting) | W(1, J) = $Z_H$ | Axial distance (hub) (dimensionless) |
| | W(2, J) = $Z_T$ | Axial distance (tip) (dimensionless) |
| | W(3, J) = $C_{PH}$ | Pressure coefficient (hub) (dimensionless) |
| | W(4, J) = $C_{PT}$ | Pressure coefficient (tip) (dimensionless) |
| | W(5, J) = $C_{FSH}$ | Friction coefficient (hub) (dimensionless) |
| | W(6, J) = $C_{FST}$ | Friction coefficient (tip) (dimensionless) |
| BCPLX (Complex Variables) | A(1,I) = $A_i$ | Source strength (dimensionless) |
| | A(2,I) = $b_i$ | Location of pole (dimensionless) |
| | A(3,I) = $\alpha_i$ | Wall angle change (deg) |
| | A(4,I) = $r_i$ | Radius in z plane (dimensionless) |
| | A(5,I) = $\phi_i$ | Angle in z plane (radians) |
| | A(6,I) = $\bar{X}_i$ | Relative x distance in z plane (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| BCPLX (Complex Variibles) | A(7,I) = $\bar{Y}_i$ | Relative Y distance in z plane (dimensionless) |
| | B(1,I,K) = $\Delta SX_s$ | Change in coordinate x (dimensionless) |
| | B(2,J,K) = $\Delta SY_s$ | Change in coordinate y (dimensionless) |
| | B(3,I,K) = $\Delta S\xi_s$ | Change in coordinate $\xi$ (dimensionless) |
| | B(4,I,K) = $\Delta S\eta_s$ | Change in coordinate $\eta$ (dimensionless) |
| | X(1,K) = S | Streamwise coordinate (dimensionless) |
| | X(2,K) = n | Normal coordinate (dimensionless) |
| | X(3,K) = X | X coordinate in z plane (dimensionless) |
| | X(4,K) = Y | Y coordinate in z plane (dimensionless) |
| | X(5,K) = $\xi$ | $\xi$ - coordinate in w plane (dimensionless) |
| | X(6,K) = $\eta$ | $\eta$- coordinate in w plane (dimensionless) |
| | X(7,K) = $\xi_s$ | Streamwise derivative of $\xi$ (dimensionless) |
| | X(8,K) = $\eta_s$ | Streamwise derivative of $\eta$ (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | X(9,K) = X(S+$\Delta$S) | Coordinates at station S+DS |
| | X(10,K) = Y(S+$\Delta$S) | Coordinates at station S+DS |
| | X(11,K) = $\xi$(S+DS) | Coordinates at station S+DS |
| | X(12,K) = $\eta$(S+DS) | Coordinates at station S+DS |
| | X(13,K) = Y | Metric scale coefficients (dimensionless) |
| | X(14,K) = $\xi_{ss}$ | Second derivative of $\xi$ (dimensionless) |
| | X(15,K) = $\xi_{sn}$ | Cross derivative of $\xi$ (dimensionless) |
| | X(16,K) = $V_n$ | Normal derivative of V (dimensionless) |
| | X(17,K) = $V_s$ | Streamwise derivative of V (dimensionless) |
| BLEED (wall bleed) | | |
| | AHAS = $A_h/A_s$ | Ratio of hole area to surface area |
| | CDISH = C | Discharge coefficient |
| | PTP = $P_{TP}$ | Plenum total pressure |
| | TTP = $T_T$ | Plenum total temperature |
| BTHIK | | |
| | KBLADE | , Number of points |
| | XK(I) = $X_I$ | , Fractional chordwise distance |
| | YK(I) = $Y_I$ | , Thickness/Chord |

I = 1, KBLADE

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| CCPLX (Parameters for Complex Transform) | NPTS = $N_p$ | Number of singularities in complex transfotmation |
| | NSØURC = $N_s$ | Number of sources in z plane |
| | ØRDER1 = $0_1$ | Absolute magnitude of largest term |
| | ØRDER2 = $0_2$ | Absolute magnitude of largest term |
| | ØRDER3 = $0_3$ | Absolute magnitude of largest term |
| | SLO = $S_{LO}$ | Length of streamwise coordinate |
| | XDS = S | Step size for complex integration |
| | XDN = S | Step size for complex integration |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| CINF (Parameters for Poisson Equation) | AMINF = $M_\infty$ | Freestream Mach number |
| | AN(K) = $n_k$ | Transverse coordinate |
| | DEDN(K) = $(d\eta/dn)_k$ | Transverse coordinate stretching |
| | D2EDN(K) = $(d^2\eta/dn^2)_k$ | Transverse coordinate stretching |
| | PINF = $\Pi_\infty$ | Freestream static pressure (dimensionless) |
| | PSIKL = $\psi_\infty$ | Freestream stream function (dimensionless) |
| | PTINF = $\Pi_\infty$ | Freestream total pressure (dimensionless) |
| | RHØINF = $\rho_\infty$ | Freestream density (dimensionless) |
| | RØTINF = $\rho_{o\infty}$ | Freestream total density (dimensionless) |
| | TEMINF = $\Theta_\infty$ | Freestream static temperature (dimensionless) |
| | TTINF = $\Theta_{o\infty}$ | Freestream total temperature (dimensionless) |
| | UINF = $U_\infty$ | Freestream velocity (dimensionless) |
| | UPINF = $U_{\phi\infty}$ | Freestream tangential velocity (dimensionless) |
| | USINF = $U_{s\infty}$ | Freestream streamwise velocity (dimensionless) |
| | UUO = $U_o$ | Reference velocity (dimensionless) |
| | VVO = $V_o$ | Reference metric coefficient |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| CØNST (Flow Constants) | ACHI = $\chi$ | | Clauser constant (0.016) |
| | AKAPPA = | K | von Karman constant (0.41) |
| | APLUS = | $A^+$ | van Driest constant (26.0) |
| | CPR = | $C_{pr}$ | Specific heat at constant pressure (5997.0 $ft^2/sec^2$/deg R) |
| | CVR = | $C_{vr}$ | Specific heat at constant volume (3283.0 $ft^2/sec^2$/deg R) |
| | EP = | 0 e | 2 .7182818 |
| | GAMMA = | $\alpha$ | Ratio of specific heats (1.4) |
| | GASR = | R - | Gas constant (1714.0 $ft^2/sec^2$/ deg R) |
| | GRAVR | | Gravitational constants (32.2 $ft/sec^2$) |
| | PI = | $\pi$ | 3.1415926 |
| | PRESR = | $P_r$ | Reference static pressure (psfa) |
| | PRL = | $Pr_L$ | Prandtl number laminar 0.70 |
| | PRT = | $Pr_T$ | Prandtl number turbulent 0.72 |
| | RHØR = | $P_r$ | Reference density ($slugs/ft^3$) |
| | SNDR = | $C_r$ | Reference speed of sound (1116.0 ft/sec) |
| | TEMPR = | Tr | Reference temperature (deg Raukine) |
| | TI | | (0.1745329 radians/deg) |
| | VISCR = | $\mu_r$ | Reference molecular viscosity (0.370 x $10^{-6}$) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| CØRE (Coordinate Functions) | $Q(1,K) = R$ | Radius (dimensionless) |
| | $Q(2,K) = Z$ | Axial distance (dimensionless |
| | $Q(3,K) = \partial R/\partial n$ | Normal derivative of radius (dimensionless) |
| | $Q(4,K) = \partial R/\partial S$ | Streamwise derivative of radius (dimensionless) |
| | $Q(5,K) = \partial^2 R/\partial n/\partial S$ | Second derivative of radius (dimensionless) |
| | $Q(6,K) = V$ | Metric scale coefficient (dimensionless) |
| | $Q(7,K) = \partial V/\partial n$ | Curvature of potential line (dimensionless) |
| | $Q(8,K) = \partial V/\partial S$ | Curvature of streamline (dimensionless) |
| | $Q(9,K) = \partial^2 V/\partial n/\partial S$ | Second derivative of metric scale coefficient (dimensionless) |
| | $Q(10,K) = Y$ | Physical distance across duct (dimensionless) |
| | $Q(11,K) = Y/Y_T$ | Fractional distance across duct (dimensionless) |
| | $Q(12,K) = A$ | Area between adjacent stream-lines (dimensionless) |
| | $Q(13,K) = G$ | Gap between blade surfaces (dimensionless) |
| | $Q(14,K) = \partial G/\partial n$ | Normal derivative of blade surface (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | $Q(15,K) = \partial G/\partial S$ | Streamwise derivative of blade surface (dimensionless) |
| | $Q(16,K) = \partial \eta/\partial n$ | Transform of normal coordinate (dimensionless) |
| | $Q(17,K) = \partial^2 \eta/\partial n^2$ | Second derivative (dimensionless) |
| | $Q(18,K) = n$ | Normal coordinate (dimensionless) |
| | $Q(19,K) = \eta$ | Transformed normal coordinate (dimensionless) |
| | $K = 1,KL$ | Number of streamlines (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| CORE 2* (Wall Value of Coordinate Functions) | RØ(1,K) = R | Radius (dimensionless) |
| | RØ(2,K) = dR/dZ | Derivative of radius (dimensionless) |
| | RØ(3,K) = $d^2R/dZ^2$ | Second derivative of radius (dimensionless) |
| | RØ(4,K) = Z | Axial distance (dimensionless) |
| | RØ(5,K) = V | Metric scale coefficient (dimensionless) |
| | RØ(6,K) = dY/dS | Derivative of metric scale coefficient (dimensionless) |
| | RØ(7,K) = $Y_T$ | Distance across duct (dimensionless) |
| | RØ(8,K) = S | Streamwise coordinate (dimensionless) |
| | RØ(9,K) = $\mathring{m}$ | Mass flow bleed (dimensionless) |
| | RØ(10,K) = $\Theta_W$ | Wall temperature (dimensionless) |
| | RØS(I) = RØ(I,K) | Dummy Storage Vector |

* Note: Actually three arrays defined where Ø takes on the value H, M, T

Ø = H, Hub wall

= M, Mean line

= T, Tip wall

| | | |
|---|---|---|
| DERIV (Force Functions) | DF(1,K) = $\left[H_s/XV\right]^J_{K-\frac{1}{2}}$ | Streamwise blade force/volume (dimensionless) |
| | DF(2,K) = $\left[H_\phi/XV\right]^J_{K-\frac{1}{2}}$ | Tangential blade force/volume (dimensionless) |
| | DF(3,K) = $\left[\Phi_B/XV\right]^J_{K-\frac{1}{2}}$ | Total pressure loss/volume (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | $DF(4,K) = \left[X\right]^{J}_{K-\frac{1}{2}}$ | Coordinate distortion (dimensionless) |
| | $DF(5,K) = \left[H_s / XV\right]^{J-1}_{K-\frac{1}{2}}$ | Streamwise blade force/volume (dimensionless) |
| | $DF(6,K) = \left[H_\phi/XV\right]^{J-1}_{K-\frac{1}{2}}$ | Tangential blade force/volume (dimensionless) |
| | $DF(7,K) = \left[\Phi_B/XV\right]^{J-1}_{K-\frac{1}{2}}$ | Total pressure loss/volume (dimensionless) |
| | $DF(8,K) = \left[X\right]^{J-1}_{K-\frac{1}{2}}$ | Coordinate distortion (dimensionless) |
| DRED1 (Store Flow Variables) | BLØCK (I) | Grid structure variables |
| | I1 = 19 * KL + 35 | |
| | I = 1, I1 | |
| DRED2 (Store Flow Variables) | BLØCK1 (I) | Grid structure variables |
| | I1 = 19 * KL + 35 | |
| | I = 1, I1 | |
| DUCØUT (Wall Coordinates) | $R(1,1,J) = R_T(Z_J)$ | Radius of hub (dimensionless) |
| | $R(2,1,J) = R_H(Z_J)$ | Radius of tip (dimensionless) |
| | $R(1,2,J) = \overset{o}{m}_T(Z_J)$ | Mass flow of tip bleed (dimensionless) |
| | $R(2,2,J) = \overset{o}{m}_H(Z_J)$ | Mass flow of hub bleed (dimensionless) |
| | $R(1,3,J) = \Theta_H(Z_J)$ | Wall temperature of tip (dimensionless) |
| | $R(2,3,J) = \Theta_T(Z_J)$ | Wall temperature of hub (dimensionless) |
| | $R(1,4,J) = Z_J$ | Axial location of hub |
| | $R(2,4,J) = Z_J$ | Axial location of tip |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| DUCTIN (Input Functions) | BINI(L) | = BINPUT(I,J,K) | , see CØMMØN/SPIØ/ |
| | I | = 1,5 | |
| | J | = 1,2 | |
| | K | = 1,KLL | |
| | L | = 5*(K-1)+I+(J-1)*5*KLL | |
| | DUCTI(I) I | = 1,15 | , Arbitrary duct geometry parameters |
| | RD1I(L) | = R(1,1,L)*RADR | , Tip wall coordinates (ft) |
| | RD2I(L) | = R(1,2,L)*RADR | , Hub wall coordinates (ft) |
| | ZD1I(L) | = R(1,4,L)*RADR | , Tip wall coordinates (ft) |
| | ZD2I(L) | = R(2,4,L)*RADR | , Hub wall coordinates (ft) |
| | L | = 1, JL | |
| DUCTIX (Input Functions) | AINI (L) | = AINDUCT (I,J,K) | , See CØMMØN/SPIØX/ |
| | L | = 1, JL | , Number of Streamwise stations |
| EBLAD (Blade Row Parameter) | NRØW | | , Maximum number of propeller Rows |
| | LRØW | | , Indicates propeller row |
| | LBLD | | , Not used |
| | NBLADE | | , Number of blades in propeller row |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| FCØR (Truncation Error Estimates) | EAP = $E_{U\phi}$ | Error in swirl velocity (dimensionless) |
| | EAS = $E_{US}$ | Error in streamwise velocity (dimensionless) |
| | EEN = $E_I$ | Error in entropy (dimensionless) |
| | EPO = $E_{PO}$ | Error in total pressure (dimensionless) |
| | ESI = $E_\psi$ | Error in stream function (dimensionless) |
| | ETO = $E_{TO}$ | Error in total temperature (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | | | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|---|---|
| FIVC (Inviscid Flow Variables I/O) | FIV(1,L,K) | = | $\psi$ | Stream function (dimensionless) |
| | FIV(2,L,K) | = | $U_s$ | Streamwise velocity (dimensionless) |
| | FIV(3,L,K) | = | $U_\phi$ | Tangential velocity (dimensionless) |
| | FIV(4,L,K) | = | $\Pi$ | Static pressure (dimensionless) |
| | FIV(5,L,K) | = | I | Entropy (dimensionless) |
| | FIV(6,L,K) | = | $\Theta$ | Static temperature (dimensionles |
| | FIV(7,L.K) | = | P | Density (dimensionless) |
| | FIV(8,L,K) | = | M | Mach number |
| | FIV(9,L,K) | = | | |
| | FIV(10,L,K) | = | | |
| | L=1 | @ | J-1 station | |
| | L=2 | @ | J station | |
| | L=3 | @ | J+1 station | |
| | K=1,KL | | streamlines | |
| | FIPARM(1) | = | $\rho_r$ | Reference density (slugs/ft$^3$) |
| | FIPARM(2) | = | $T_r$ | Reference temperature (deg R) |
| | FIPARM(3) | = | $P_r$ | Reference pressure (psfa) |
| | FIPARM(4) | = | g | Gravitational constant (ft/sec$^2$ |
| | FIPARM(5) | = | $\mu_r$ | Reference viscosity (slugs/ft/sec) |
| | FIPARM(6) | = | $C_p$ | Specific heat constant pressure (ft$^2$/sec$^2$/deg) |
| | FIPARM(7) | = | $C_v$ | Specific heat constant volume (ft$^2$/sec$^2$/deg) |
| | FIPARM(8) | = | R | Gas constant (ft$^2$/sec$^2$/deg) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | | DESCRIPTION OF VARIABLES |
|---|---|---|---|---|
| | FIPARM(9) | = | $Pr_T$ | Prandtl number (turbulent) |
| | FIPARM(10) | | | |
| | FIPARM(11) | = | $u_r$ | Reference velocity (ft/sec) |
| | FIPARM(12) | | NØPT7 | Number of stations stored in inviscid solver |
| | FIPARM(13) | | | |
| | FIPARM(14) | | IØPT15 | First station |
| | FIPARM(15) | | IØPT16 | Last station |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| FLAGS (Flags) | NØPTØ Ø = 1,28 | Flags to regulate calculation flow (see subroutines) |
| FLØWI (Flow Input Functions) | FG(1,K) = $\alpha$ | Inlet swirl angle (deg) |
| | FG(2,K) = $\Pi_o$ | Inlet stagnation pressure (dimensionless) |
| | FG(3,K) = $\Theta_o$ | Inlet stagnation temperature (dimensionless) |
| | FG(4,K) = M | Inlet Mach number (dimensionless) |
| | FG(5,K) = $P_o$ | Inlet stagnation density (dimensionless) |
| | FG(6,K) = U | Inlet magnitude of velocity (dimensionless) |
| | K = 1, KL | Number of streamlines |
| FØRS (Blade Force Variables) | FØRC(1,K) = $H_s$ | Streamwise force/area (dimensionless) |
| | FØRC(2,K) = $H_\phi$ | Swirl force/area (dimensionless) |
| | FØRC(3,K) = $\Xi_s$ | Streamwise force/span (dimensionless) |
| | FØRC(4,K) = $\Xi_\phi$ | Swirl force/span (dimensionless) |
| | FØRC(5,K) = $\Phi_B$ | Blade dissipation/area (dimensionless) |
| | FORC(6,K) = | Blade dissipation/span (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| FORS2 (Blade Force Variables) | | |
| | FF(1,I,K) = $\hat{M}$ | Inviscid Mach number (dimensionless) |
| | FF(2,I,K) = $\hat{\Pi}$ | Inviscid static pressure (dimensionless) |
| | FF(3,I,K = $\hat{\theta}$ | Inviscid static temperature (dimensionless) |
| | FF(4,I,K) = $\hat{\theta}_o$ | Inviscid total temperature (dimensionless) |
| | FF(5,I,K) = $\hat{\Pi}_o$ | Inviscid total pressure (dimensionless) |
| | FF(6,I,K) = $\hat{\rho}$ | Inviscid density (dimensionless) |
| | FF(7,I,K) = $\hat{U}_S$ | Inviscid streamwise velocity (dimensionless) |
| | FF(8,I,K) = $\hat{U}_\phi$ | Absolute swirl velocity (dimensionless) |
| | FF(9,I,K) = $\hat{W}_\phi$ | Relative swirl velocity (dimensionless) |
| | FF(10,I,K) = $\hat{U}_B$ | Blade velocity (dimensionless) |
| | FF(11,I,K) = $\hat{\alpha}$ | Absolute angle to axis (deg) |
| | FF(12,I,K) = $\hat{\beta}$ | Relative angle to axis (deg) |
| | FF(13,I,K) = $\hat{I}$ | Inviscid flow entropy (dimensionless) |
| | FF(14,I,K) = $\hat{U}$ | Magnitude of relative inviscid flow velocity (dimensionless) |

(Continued)

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| FORS2 (Blade Force Variables) | | | |
| | FF(15,I,K) | $= \hat{Z}_B$ | Loss coefficient (dimensionless) |
| | FF(15,2,K) | $= \Delta\hat{I}_B$ | Blade entropy rise (dimensionless) |
| | FF(16,I,K) | $= \hat{\psi}$ | Stream function (dimensionless) |
| | FF(17,1,K) | $= C_L$ | Lift coefficient (dimensionless) |
| | FF(17,2,K) | $= C_D$ | Drag coefficient (dimensionless) |
| | I | = 1 | Upstream of blade row |
| | I | = 2 | Downstream of blade row |
| | K | = 1, KL | Number of streamlines |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | K = 1,KL | Number of streamlines (dimensionless) |
| FUNC (Dependent Flow Variables) | F(1,I,K) = $\psi$ | Stream function (dimensionless) |
| | F(2,I,K) = $U_S$ | Streamwise velocity (dimensionless) |
| | F(3,I,K) = $U_\phi$ | Swirl velocity (dimensionless) |
| | F(4,I,K) = $\Pi$ | Static pressure (dimensionless) |
| | F(5,I,K) = I | Entropy (dimensionless) |
| | F(6,I,K) = $\Theta$ | Static temperature (dimensionless) |
| | F(7,I,K) = P | Density (dimensionless) |
| | F(8,I,K) = $\Sigma_{ns}$ | Streamwise stress (dimensionless) |
| | F(9,I,K) = $\Sigma_{n\phi}$ | Swirl stress (dimensionless) |
| | F(10,I,K) = Q | Heat flux (dimensionless) |
| | I = 1 | Inlet conditions |
| | I = 2 | S=S |
| | I = 3 | S=S+dS |
| | K = 1, KL | Number of streamlines |
| INTINP (Integer Input Variables) | IØPTØ = 1, 17 | Input/Output options |
| | IDBGØ = 1, 23 | Debug printout options |
| | ISHAPE | Blade shape option |
| | JL | Number of streamwise stations |
| | KDS | Number of steps per streamwise station |
| | KL | Number of streamlines |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | KLL | Number of input data streamlines |
| | NB | Number of blades |

INTPAR (Parameter Variables)

These variables are treated as PARAMETER statements in UNIVAC programs and as integer variables in IBM or CDC programs.

Parameters for Solution Arrays

```
PARAMETER IST = 100
PARAMETER IS  = 100
PARAMETER NEQ = 10
PARAMETER NBCH = 5
PARAMETER NBCT = 5
PARAMETER NBH1 = NBCH+1 = 6
PARAMETER NEQD = 2*NEQ = 20
```

Parameters for Slots

```
PARAMETER ISLØT = 15
PARAMETER ISLØT2 = 2*ISLØT = 30
PARAMETER IS1 = 6*ISLØT+2 = 92
PARAMETER IS2 = 2*IS+IS1 = 292
```

Parameters for Coordinate Arrays

```
PARAMETER ISM = 19*IST = 1900
PARAMETER ISL = ISM+35 = 1935
PARAMETER IS3 = ISM+2  = 1902
PARAMETER IS4 = IS3+10 = 1912
PARAMETER IS5 = IS4+10 = 1922
PARAMETER IS6 = IS5+10 = 1932
```

Parameters for Matrix Inversion

```
PARAMETER KKLP = 30
PARAMETER LNGTØ = NEQ*NEG*KKLP+NEQ*KKLP = 3300
PARAMETER LNGT1 = NEQ*NEQ*KKLP+1 = 3001
PARAMETER LNGT2 = 2*LNGTO = 6600
PARAMETER LNGT3 = 3*IST*NEQ = 3000
```

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|

Parameters for Force Variables

PARAMETER IFFS = 34*IST = 3400

Parameters for Smooth

PARAMETER ISSD = 20
PARAMETER ISSD1 = ISSD+1 = 21
PARAMERER ISSD2 = ISSD1+ISSD = 41
PARAMETER ISSD3 = ISSD2+ISSD = 61

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| REALIN (Real Input Variables) | ACI | $= \chi$ | Clauser constant |
| | AKI | $= \kappa$ | von Karman constant |
| | ALP1 | $= \alpha_1$ | Inlet swirl angle hub (deg to z axis) |
| | AMS1 | $= M_1$ | Inlet Mach number (dimensionless) |
| | ANH | $= n_H$ | Power law of hub boundary layer |
| | ANT | $= n_T$ | Power law of tip boundary layer |
| | API | $= A^+$ | van Driest constant |
| | CPRI | $= C_{P_r}$ | Specific heat constant pressure ($ft^2/sec^2$/deg R) |
| | CVRI | $= C_{V_r}$ | Specific heat constant volume ($ft^2/sec^2$/deg R) |
| | DDS | = | Mesh distortion parameter |
| | DSHI | $= \delta_H^*$ | Displacement thickness hub (ft) |
| | DSTI | $= \delta_T^*$ | Displacement thickness tip (ft) |
| | PRESO | $= P_{01}$ | Inlet stagnation pressure |
| | PRLI | $= P_{RL}$ | Prandtl number laminar |
| | PRTI | $= P_{RT}$ | Prandtl number turbulent |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| | TEMPO | $= T_{01}$ | Inlet stagnation temperature (deg R) |
| | VISCRI | $= \mu_r$ | Molecular viscosity reference (lb/sec $ft^3$) |
| REALIX (Real Input Variables) | ALPHSI | $= \alpha_{CH}$ | Blade stagger angle hub (deg to z axis) |
| | ALPSMI | $= \alpha_{CM}$ | Blade stagger angle mid (deg to z axis) |
| | ALPSTI | $= \alpha_{CT}$ | Blade stagger angle tip (deg to z axis) |
| | CØRDHI | $= B_H$ | Blade chord hub (ft) |
| | CØRDMI | $= B_\mu$ | Blade chord midpoint (ft) |
| | CØRDTI | $= B_T$ | Blade chord tip (ft) |
| | PHICHI | $= \phi_{CH}$ | Blade camber hub (deg) |
| | PHICMI | $= \phi_{CM}$ | Blade camber midpoint (deg) |
| | PHICTI | $= \phi_{CT}$ | Blade camber tip (deg) |
| | RCLHI | $= r_{CLH}$ | Hub radius of blade centerline (ft) |
| | RCLMI | $= r_{CLM}$ | Midpoint radius of blade centerline (ft) |
| | RCLTI | $= r_{CLT}$ | Tip radius of blade centerline (ft) |
| | THIKHI | $= t_H/B_H$ | Blade thickness to chord ratio hub (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | THIKMI $= t_M/B_M$ | Blade thickness to chord ratio midpoint (dimensionless) |
| | THIKTI $= t_T/B_T$ | Blade thickness to chord ratio tip (dimensionless) |
| | ZCLHI $= Z_{CLH}$ | Blade Axial location of center-line (Hub) |
| | ZCLMI $= Z_{CLM}$ | Blade axial location of center-line (Midpoint) |
| | ZCLTI $= Z_{CLT}$ | Blade axial location of center-line (Tip) |
| | ZCLI $= Z_{CL}$ | Blade centerline location (ft) |
| SPCFD (Variables in Poisson Equation) | F(K,J) $= 1/(P\ V)_K^J$ | Coefficients of Poisson equation |
| | P(K,J) $= \Psi_K^J$ | Stream function |
| SPCGD (Variables for Streamline Curvature) | F(K) $= 1/(P\ V)_K$ | Coefficient of Poisson equation |
| | G(K) $= V/(G\ )_K$ | Coefficient for velocity |
| | P(K) $= \ _K$ | Density ratio $(\rho/\rho_r)$ |
| | T(K) $= \ _K$ | Temperature ratio $(T/T_r)$ |
| | V(K) $= V_K$ | Metric coefficient |
| SPIØ (Flow Variables) | AVE(1,J) $= \bar{Z}$ | Average axial location (dimensionless) |
| | AVE(2,J) = AR | Area ratio (dimensionless) |
| | AVE(3,J) $= \psi$ | Mass flow (dimensionless) |
| | AVE(4,J) $= \bar{U}_S$ | Average streamwise velocity (dimensionless) |
| | AVE(5,J) $= \bar{U}_\emptyset$ | Average swirl velocity (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | AVE(6,J) = $\Pi$ | Average entropy (dimensionless) |
| | AVE(7,J) = $\bar{I}$ | Average entropy (dimensionless) |
| | AVE(8,J) = $\bar{\theta}$ | Average static temperature (dimensionless) |
| | AVE(9,J) = $\bar{\rho}$ | Average density (dimensionless) |
| | AVE(10,J) = $\bar{M}$ | Average Mach number (dimensionless) |
| | AVE(11,J) = $\bar{\Pi}_o$ | Average total pressure (dimensionless) |
| | AVE(12,J) = $\bar{\theta}_o$ | Average total temperature (dimensionless) |
| | AVE(13,J) = $\bar{C}p$ | Average pressure coefficient (dimensionless) |
| | AVE(14,J) = $\bar{C}p_1$ | Average total pressure loss (dimensionless) |
| | AVE(15,J) = Z | Diffuser effectiveness (dimensionless) |
| | AVE(16,J) = B | Blockage (dimensionless) |
| | AVE(17,J) = $\tilde{M}$<br>J = 1, JL | Area average Mach number (dimensionless) |
| | BINPUT(1,J,K) = Y | Spanwise location (dimensionless) |
| | BINPUT(2,J,K) = $\Pi_o$ | Total pressure (lb/ft$^2$ abs) |
| | BINPUT(3,J,K) = $\Pi$ | Static pressure (lb/ft$^2$ abs) |
| | BINPUT(4,J,K) = $\alpha$ | Swirl angle (deg to axis) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | DESCRIPTION OF VARIABLES |
|---|---|---|
| | BINPUT(5,J,K) = $\Theta_o$ | Total temperature (deg R) |
| | J = 1 | Inlet flow |
| | J = 2 | Exit flow |
| | K = 1, KLL | Number of spanwise stations |
| SPIØX (Flow Variables) | AINPUT(1,J,K) = Y | Spanwise location (dimensionless) |
| | AINPUT(2,J,K) = $\Pi_O$ | Total pressure ($lb/ft^2$ abs) |
| | AINPUT(3,J,K) = $\Pi$ | Static pressure ($lb/ft^2$ abs) |
| | AINPUT(4,J,K) = $\alpha$ | Swirl angle (deg to axis) |
| | AINPUT(5,J,K) = $\Theta_o$ | Total temperature (deg R) |
| | J = 1 | Upstream of blade row (dimensionless) |
| | J = 2 | Downstream of blade row (dimensionless) |
| | K = 1, KLL | Number of spanwise stations |
| STRMES (Poisson Stretching Parameter) | BPØIS = B | Stretching parameter |
| | BPØISI = $B_I$ | Input stretching parameter |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| STRES (Functions of Orthogonal Coordinates) | G(1,K) | $= \left[G/V\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(2,K) | $= \left[XY\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(3,K) | $= \left[G(XV)\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(4,K) | $= \left[\frac{1}{XV}\frac{\partial V}{\partial n}\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(5,K) | $= \left[\frac{1}{XR}\frac{\partial R}{\partial n}\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(6,K) | $= \left[\frac{1}{XR}\frac{\partial R}{\partial S}\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(7,K) | $= \left[\frac{V}{XG}\frac{\partial}{\partial n}\left(\frac{G}{V}\right)\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(8,K) | $= \left[\frac{V}{XG}\frac{\partial}{\partial n}\left(\frac{G}{V}\right)-\frac{1}{XY}\frac{\partial V}{\partial n}\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(9,K) | $= \left[\frac{V}{XG}\frac{\partial}{\partial n}\left(\frac{G}{V}\right)-\frac{1}{XR}\frac{\partial R}{\partial n}\right]^{J}_{K-\frac{1}{2}}$ | |
| | G(9+I,K) K = 1,KL | = G(I,K) @ J-1, I=1,9 | |
| SVARB (Parameters and Variables) | ALPHS | $= \alpha$ | Stagger angle to axis (deg) |
| | ALPLUM | = | Not used in this version |
| | AMACHR | $= M_r$ | Reference Mach number (dimensionless) |
| | AMACH1 | $= \bar{M}_1$ | Average inlet Mach number (dimensionless) |
| | AMPLUM | = | Not used in this version |
| | AMPLUS | $= M^+$ | Mass flow bleed parameter (dimensionless) |
| | APRES1 | $= \bar{P}_1$ | Average inlet static pressure (dimensionless) |
| | AREA1 | $= A_1$ | Inlet area ($ft^2$) |
| | AREAR | $= A_r$ | Reference area ($ft^2$) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| | ATEMP1 | $= \bar{T}_1$ | Average inlet static pressure (dimensionless) |
| | CHØRD | $= B$ | Local strut chord (dimensionless) |
| | DETA | $= \Delta\eta$ | Step size in normal coordinate (dimensionless) |
| | DMPULS | $= \Delta m^+$ | Step size in asymptotic constant table ($m^+$) (dimensionless) |
| | DPLUSM | $= \Delta P^+$ | Step size in asymptotic constant table ($p^+$) (dimensionless) |
| | DS | $= \Delta S$ | Streamwise step size between stations (dimensionless) |
| | DSH | $= \Delta_H^*$ | Displacement thickness hub (dimensionless) |
| | DSS | $= dS$ | Streamwise step size (dimensionless) |
| | DST | $= \Delta_T^*$ | Displacement thickness tip (dimensionless) |
| | DZ | $= \Delta Z$ | Axial step size (dimensionless) |
| | DYNP1 | $= Q_1$ | Average inlet dynamic pressure (dimensionless) |
| | GAP | $= G$ | Gap between blades (dimensionless) |
| | GMR1 | $= (\gamma^{-1})M_r^2$ | |
| | GMR2 | $= \gamma M_r^2$ | |
| | JLAST | = | Number of streamwise stations |
| | JLPTS | = | Number of input wall points |
| | JSEP | = | Number of stations to last calculated point |
| | KMH | = | Hub matching point |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| | KMT | = | Tip matching point |
| | KMO | = | Not used in this version |
| | KSEP | = | Not used in this version |
| | LM | = | Size of table of constants for inner layer (dimensionless) |
| | LMM | = | Midpoint of table of constants for inner layer (dimensionless) |
| | PHIC | = $\phi_c$ | Blade camber (deg) |
| | PLUSM | = | Not used in this version |
| | PPLUS | = $P^+$ | Pressure gradient parameter (dimensionless) |
| | RADR | = $r_r$ | Reference radius of blade centerline (dimensionless) |
| | REY | = $N_R$ | Reynolds number $P_r R_r U_r / U_r$ |
| | RHØR | = $P_r$ | Reference density (slugs/ft$^3$) |
| | SL | = $S_L$ | Length of duct in streamline coordinates (dimensionless) |
| | SØLD | = $\sigma$ | Solidity (dimensionless) |
| | THICK | = t | Local blade thickness (dimensionless) |
| | USTARH | = $U_H^*$ | Friction velocity hub (dimensionless) |
| | USTART | = $U_T^*$ | Friction velocity tip (dimensionless) |
| | USR | = $U_r$ | Reference radius (dimensionless) |
| | WFLØ | = | Weight flow (lb/sec) |
| | YPLUSM | = | Matching point for table asymptotic constants (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| | ZLE | = | Axial location of blade trailing edge (demensionless) |
| | ZTE | = | Axial location of blade leading edge (dimensionless) |
| | Z1 | = | Duct axial length (dimensionless) |
| SVARBX (Blade Variables) | ALPSH | = $\alpha_H$ | Hub stagger angle to axis (deg) |
| | ALPSM | = $\alpha_M$ | Midpoint stagger angle to axis (deg) |
| | ALPST | = $\alpha_T$ | Tip stagger angle to axis (deg) |
| | CHØRDH | = $B_H$ | Blade chord hub (dimensionless) |
| | CHØRDM | = $B_M$ | Blade chord midpoint (dimensionless) |
| | CHØRDT | = $B_T$ | Blade chord tip (dimensionless) |
| | PHICH | = $\phi_{CH}$ | Blade camber - hub (deg) |
| | PHICM | = $\phi_{CM}$ | Blade camber - midpoint (deg) |
| | PHICT | = $\phi_{CT}$ | Blade camber - tip (deg) |
| | RCLM | = $R_{CLM}$ | Midpoint radius of blade center (dimensionless) |
| | RCLT | = $R_{CLT}$ | Tip radius of blade centerline (dimensionless) |
| | RCLH | = $R_{CLH}$ | Midpoint radius of blade center (dimensionless) |
| | THICKH | = $t_H$ | Blade thickness hub (dimensionless) |
| | THICKM | = $t_M$ | Blade thickness midpoint (dimensionless) |
| | THICKT | = $t_T$ | Blade thickness tip (dimensionless) |

| COMMON BLOCK NAME (OBJECT) | VARIABLE NAME | | DESCRIPTION OF VARIABLES |
|---|---|---|---|
| | ZCLH | $= Z_{CLH}$ | Hub axial location of blade center line |
| | ZCLM | $= Z_{CLM}$ | Midpoint axial location of blade centerline |
| | ZCLT | $= Z_{CLT}$ | Tip axial location of blade centerline |
| | ZCL | $= Z_{CL}$ | Axial distance to blade center-line (dimensionless) |
| TITLIN (Input Title) | TITLE(12) | | Any alphanumeric characters |
| TURBS (Turbulent Viscosity and Conductivity) | DHF(1,K) | $= \frac{\partial}{\partial \iota}\left(\frac{\mu_E}{\mu_J}\right)^{J-1}_{K-\frac{1}{2}}$ | Derivative of viscosity |
| | DHF(2,K) | $= (\mu_T/\mu_r)^{J-1}_{K-\frac{1}{2}}$ | Turbulent viscosity (dimensionless) |
| | DPF(1,K) | = | |
| | DPF(2,K) | $= (\frac{1}{P_{RE}} \frac{\mu_r}{\mu_r})^{J-1}_{K-\frac{1}{2}}$ | Turbulent conductivity (dimensionless) |

K = 1, KL

List of Flags NØPTØ

| Flag Name | Purpose |
|---|---|
| NØPT1=0 | Setup initial flow |
| NØPT1=1 | Calculate flow at station J |
| NØPT2=1 | Adiabatic wall |
| NØPT2=2 | Wall heat transfer |
| NØPT3=1 | Compute and store coordinate functions |
| NØPT3=2 | Compute local coordinate functions |
| NØPT4=0 | Duct with centerbody |
| NØPT4=1 | Duct with no centerbody |
| *NØPT5=0 | Continue calculating |
| NØPTS>0 | Stop calculating |
| NØPT6 | Not used |
| NØPT7=1 | Flow separated from tip wall |
| NØPT7=2 | Flow separated from hub wall |
| NØPT8=0 | Read inviscid flow variables |
| NØPT8=1 | Read viscous flow variables |
| NØPT9=0 | Full complex function calculation |
| NØPT9=1 | Shorten complex function calculation |
| NØPT10= | Counts number of cases calculated |
| NØPT11=0 | Computer graphics I/O |
| NØTP11=1 | Batch I/O |

*NØPT5 is given a value to locate error in program
In addition, a diagnostic message is printed.

| | |
|---|---|
| NØPT13 | FCPLX flag |
| NØPT14=0 | UNIVAC |
| NØPT14=1 | IBM |
| NØTP15=0 | Integrate along S to obtain streamline |
| NØPT15=1 | Integrate along n to obtain streamline |
| NØPT16 | Station counter |
| NØPT17=0 | No blade force calculation |
| NØPT17=1 | Compute blade force |
| NØPT18=0 | Turbulent flow |
| NØPT18=1 | Laminar flow |
| NØPT19=INFL1 | NFLO iteration in subroutine FLØWIN |
| NØPT20=0 | Optimize KDS |
| NØPT20=1 | Fix KDS |
| NØPT21=0 | Greater than critical Reynolds number |
| NØPT21=1 | Less than critical Reynolds number |
| NØPT22=0 | Stator |
| NØPT22=1 | Rotor |
| NØPT22=2 | Propeller |

## APPENDIX A

### Sample Input Setups

The input data to three sample cases is shown in this section to demonstrate how the input data must be structured in order for the PANPER analysis program to operate correctly. To illustrate the setup of the data input for certain modes of operation of the PANPER program, three different setups are shown. The three setups are:

(1) Isolated Propeller Configuration

(2) Combined Propeller-Nacelle Configuration

(3) Combined Coaxial Propeller-Nacelle Configuration

The job control language (JCL) and the sample data input for each of these configurations are shown in Tables (II), (III), and (IV), respectively. The JCL commands are for a UNIVAC 1110 operating system. An isolated nacelle configuration is essentially the same as the second configuration (Table III) with the appropriate changes in the mode control input and the removal of the propeller input data.

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE II

JCL AND INPUT DATA SETUP FOR ISOLATED
PROPELLER CONFIGURATION

```
@ASG,T 1
@ASG,T 2
@ASG,T 3
@ASG,T 4
@ASG,T 30
@XQT,RZ PANPER.PROPF2
-1 0
INPUT
STN     11.
DEBUG   1.
WAKEOP  0.0
WAKNAC  0.0
COMPRS  1.0
CNSECT  1.0
RDCAS1  .367
TYPESL  0.0
EVAARD  1.0
VORCOR  .005
SKINOP  1.0
STACK   .25
CASCAD  1.0
ROLUP1  0.0
TRUCT1  0.0
TRUCI1  0.0
SOLVEM  0.0
CBWAKE  0.0
COFLOW  0.0
VKTAS   521.3
RPM     8440.0
SOUND   1111.08
DENSTY  .001850
VIMOM1  -25.79
BLADEN  8.0
PROPNM  1.0
RAD1    1.020833
THETA1  58.509
DCPDT   .3
DCTDT   0.0
CPI     1.653
CTI     0.0
HUBQ1   0.0
DPSI    15.0
REV     2.0
ZHUB    0.0
END
BLADE
12
XSB
 .2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755,.8571,.9388,.9796,1.0
ZSB
 .019105,.017982,.015686,.013321,.009513,.004623,.001033,.0000597
 .003047,.010756,.018116,.024321
YSB
  .055174,.056043,.058505,.063162,.062463,.049191,.027389,-.0034893
 -.042912,-.089396,-.124773,-.154588
XMC
1.
ZMC
 .02045
YMC
-.12999
END
VARDAT
AIHN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
23.1,23.1,23.1,23.1,23.1,23.1,23.1,23.1
23.1,23.1,23.1,23.1
THET
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
19.099,17.789,15.009,11.908,8.659,5.369,2.159,-.981
-4.061,-6.861,-8.261,-8.941
DECL
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
-.367,-.263,-.060,.075,.170,.188,.160,.115
.064,.025,.010,.008
CORD
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.2863,.2903,.2980,.3004,.2977,.2926,.2891,.2829
.2697,.2357,.1895,.1017
TOVC
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.212,.111,.07,.045,.04,.033,.028,.025
.022,.021,.0205,.02
VOVD
4
0.0,.3,.6,1.
1.0,1.0,1.0,1.0
URVD
4
0.0,.3,.6,1.
0.0,0.0,0.0,0.0
SOUN
4
0.0,.3,.6,1.
1.0,1.0,1.0,1.0
DENS
4
0.0,.3,.6,1.
1.0,1.0,1.0,1.0
END
```

TABLE III

JCL AND INPUT DATA SETUP FOR SINGLE
PROPELLER-NACELLE CONFIGURATION

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```
@ASG,T    8,F/200/TRK/250
@USE      9,ACOMP.
@ASG,T   10,D/60000/TRK
@ASG,T   11,D/50000/TRK
@ASG,T   12,D/60000/TRK
@ASG,T   13,D/6160/TRK
@ASG,T   14,D/60000/TRK
@ASG,T   15,D/10400/TRK
@ASG,T   16,D/5560/TRK
@ASG,T 1
@ASG,T 2
@ASG,T 3
@ASG,T 4
@ASG,T 30
@USE      20,BCOMP.
@XQT,RZ   SWAFDH,PROPF2
 1 1
INPUT
STN      11.
DEBUG    1.
WAKEOP   1.0
WAKNAC   1.0
COMPRS   1.0
CNSECT   1.0
RDCAS1   .367
TYPESL   0.0
EVAARD   1.0
VORCOR   .005
SKINOP   1.0
STACK    .25
CASCAD   1.0
ROLUP1   0.0
TRUCT1   0.0
TRUCI1   0.0
SOLVEM   0.0
CBWAKE   0.0
COFLOW   0.0
VKTAS    521.3
RPM      8440.0
SOUND    1111.08
DENSTY   .001850
VIMOM1   -25.79
BLADEN   8.0
PROPNM   1.0
RAD1     1.020833
THETA1   58.509
DCPDT    .3
DCTDT    0.0
CPI      1.653
CTI      0.0
HUB01    0.0
DPSI     15.0
REV      2.0
ZHUB     0.0
END
BLADE
12
XSB
 .2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755,.8571,.9388,.9796,1.0
ZSB
 .019105,.017982,.015686,.013321,.009513,.004623,.001033,.0000597
 .003047,.010756,.018116,.024321
YSB
 .055174,.056043,.058505,.063162,.062463,.049191,.027389,-.0034893
 -.042912,-.089396,-.124773,-.154588
XMC
1.
ZMC
 .02045
YMC
-.12999
END
VARDAT
AIRN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
23.1,23.1,23.1,23.1,23.1,23.1,23.1,23.1
23.1,23.1,23.1,23.1
THET
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
19.099,17.789,15.009,11.908,8.659,5.369,2.159,-.981
-4.061,-6.861,-8.261,-8.941
DECL
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
-.367,-.263,-.060,.075,.170,.188,.160,.115
.064,.025,.010,.008
CORD
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.2863,.2903,.2980,.3004,.2977,.2926,.2891,.2829
.2697,.2357,.1895,.1017
TOVC
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.212,.111,.07,.045,.04,.033,.028,.025
.022,.021,.0205,.02
DENS
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.9676,.973,.9788,.9827,.9849,.9865,.9881,.9903
.9916,.9935,.9946,.9946
SOUN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.9939,.9946,.9956,.9965,.9972,.9978,.9981,.9983
.9985,.999,.9991,.9992
URVO
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.384,.352,.301,.25,.216,.188,.165,.148
.133,.119,.114,.109
VOVO
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9386,.9796,1.0
.967,.975,.986,.996,.999,1.,1.001,1.001
1.001,1.001,1.001,1.001
END
PROPFAN MODEL 1 BASELINE
 3 3 2-1 0 0 0 0 3 2 0      4200 1 0        0 1                    1
              45100  5 15  0 81  0
   5.4167    20.
 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
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 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
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 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
 3.9088
  .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517
  .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517
  .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517
  .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517
  .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517   .0153517
   .043780    .081343    .108552    .132622    .156376    .180139    .203901    .227664
   .251427    .275189    .298952    .321979    .339755    .350193    .357232    .361008
   .362325    .361529    .358927    .354890    .349788    .343991    .337869    .331792
   .326130    .321311    .317848    .315624    .314498    .316445    .320144    .323843
   .327541    .331240    .334939    .338637    .342336    .346035    .349733    .353432
   .357131
   0.79200    0.00000    0.00060    0.00100   10.0000    10.0000
    3.2625   8   7 12 8440.     001001
  2462.72    577.
```

TABLE IV

JCL AND INPUT DATA FOR COAXIAL
PROPELLER-NACELLE CONFIGURATION

```
@ASG,T    8,F/20C/TRK/250
@USE      9,ACOMP.
@ASG,T   10,D/60000/TRK
@ASG,T   11,D/50000/TRK
@ASG,T   12,D/6C000/TRK
@ASG,T   13,D/6160/TRK
@ASG,T   14,D/60000/TRK
@ASG,T   15,D/10400/TRK
@ASG,T   16,D/5560/TRK
@ASG,T 1
@ASG,T 2
@ASG,T 3
@ASG,T 4
@ASG,T 30
@USE     20,BCOMP.
@PACK PANPER
@XQT,RZ PANPER.PROPF2
 1 0
INPUT
STN       11.
COMPRS 1.0
WAKNAC 1.
WAKEOP 1.
DEBUG  1.
CNSECT 1.0
RDCAS1 .367
RDCAS2 .367
EVAARD 1.0
VORCOR .005
SKINOP 1.0
STACK  .49
CASCAD 1.0
VKTAS  461.2
RPM    7490.0
SOUND  973.0
DENSTY .000736
VIMOM1 -17.0
VIMOM2 -25.0
BLADEN 4.0
PROPNM 2.0
RAD1   1.020833
RAD2   1.020833
THETA1 59.0
THETA2   56.0
DPSI   11.25
REV    1.0
ZHUB   .2
END
BLADE
12
XSB
 .2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755,.8571,.9388,.9796,1.0
ZSB
 .026,.0308,.0336,.0301,.0211,.0103,.0024,-.0001,.0046,.0177,.0271,.0326
YSB
 .0675,.0899,.123,.1432,.1418,.114,.0689,.0066,-.0719,-.165,-.216,-.243
XMC
1.
ZMC
 .02045
YMC
-.12999
END
VARDAT
AIRN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
23.1,23.1,23.1,23.1,23.1,23.1,23.1,23.1
23.1,23.1,23.1,23.1
THET
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.C
19.079,17.764,14.969,11.308,8.574,5.234,1.944,-1.301
-4.511,-7.546,-9.091,-9.841
DECL
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
-.367,-.263,-.060,.075,.170,.188,.160,.115
.064,.025,.010,.008
CORD
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.C
.2863,.2903,.2980,.3004,.2977,.2926,.2891,.2829
.2697,.2357,.1895,.1017
TOVC
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.212,.111,.07,.045,.04,.033,.028,.025
.022,.021,.0205,.02
DENS
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.9688,.9728,.9783,.9647,.9715,.9769,.981C,.9823
.9742,.981,.981,1.0
SOUN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.9937,.9947,.9957,.9929,.9943,.9953,.9962,.9966
.9949,.9957,.9964,.9964
URVO
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.3867,.3408,.2892,.2466,.2111,.1872,.1638,.1551
.1262,.1145,.1088,.1059
VOVO
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.974,.983,.992,1.02,1.02,1.02,1.02,1.01
1.03,1.03,1.02,1.02
END
BLADE
12
XSB
 .2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755,.8571,.9388,.9796,1.0
ZSB
 .026,.0308,.0336,.0301,.0211,.0103,.0024,-.0001,.0046,.0177,.0271,.0326
YSB
 .0675,.0899,.123,.1432,.1418,.114,.0689,.0066,-.0719,-.165,-.216,-.243
XMC
1.
ZMC
 .02425
YMC
-.2083
END
VARDAT
AIRN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
23.1,23.1,23.1,23.1,23.1,23.1,23.1,23.1
23.1,23.1,23.1,23.1
THET
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
23.9,20.9,16.5,12.4,8.70,5.3, 2.1,-.9
-3.7,-6.0,-7.0,-7.5
DECL
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
-.36,-.17,.035,.13,.167,.195,.218,.234
.234,.223,.21,.204
CORD
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9386,.9796,1.0
.3633,.368,.384,.403,.405,.396,.3781,.348
.301,.2262,.1774,.145
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
TOVC
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.C
.24,.114,.0675,.051,.0405,.0327,.027,.0233
.0211,.02,.02,.C2
DENS
12
.2392,.2657,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.9688,.9726,.9783,.9647,.9715,.9769,.981C,.9823
.9742,.9810,.9810,1.0
SOUN
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.C
.9937,.9947,.9957,.9929,.9943,.9953,.9962,.9966
.9949,.9957,.9964,.9964
URVO
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.3867,.3408,.2892,.2466,.2111,.1672,.1638,.1551
.1262,.1145,.1088,.1059
VOVC
12
.2392,.2857,.3673,.4490,.5306,.6122,.6939,.7755
.8571,.9388,.9796,1.0
.974,.983,.992,1.02,1.02,1.02,1.02,1.01
1.03,1.03,1.02,1.02
ENC
PROPFAN MODEL 1 COAXIAL
 3 3 2-1 0 0 0 0 3 2 0      4200 1 0         0 1                        1
           45100   5 15  0 81  0
   5.4167    20.
 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000 3.9088000
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 3.9088
  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517
  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517
  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517
  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517
  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517  .0153517
   .043760   .081343   .108552   .132622   .156376   .180139   .203901   .227664
   .251427   .275189   .298952   .321979   .339055   .350193   .357232   .361008
   .362325   .361529   .358927   .354890   .349788   .343991   .337869   .331792
   .326130   .321311   .317848   .315624   .314498   .316445   .320144   .323843
   .327541   .331240   .334939   .338637   .342336   .346035   .349733   .353432
   .357131
  0.79200   0.00000   0.00060   0.00100   10.0000   10.0000
   3.2625   4   7 12 8440.      001002
   3.4625   4   7 12 8440.      002002
 2462.72    577.
```

## APPENDIX B

### Example of PANPER Analysis Program Output

The purpose of this appendix is to give an example of the printout that is output from the PANPER analysis program for the case. The case which is used to demonstrate this printout is the analysis of a nacelle-propeller configuration (Table III). This type of configuration was used as a test case in reference 1. The entire printout from this sample case will not be included in this appendix but rather specific areas of the printout are listed in order to illustrate the output of the various tasks that the program performs. Printout will be shown for the following tasks:

(1) Main Program Heading and Output of Initial Propeller Input Data

(2) Output of the Options and Input Data used in Nacelle Analysis

(3) Output of the Nacelle Geometry

(4) Output of the Inviscid Flow Solution (At Axial Station ZH = .76489)

(5) Output of the Lifting Line Noninduced Inflow Conditions

(6) Output of the Options and Reference Data used in Propeller Analysis

(7) Output of Selected Intermediate Calculation Results for the Propeller Analysis

(8) Output of the Propeller Performance Results

(9) Output of the Propeller Blade Forces

(10) Output of the Nacelle Viscous Flow Solution (At Axial Station ZH = .76489)

(1) Main Program Heading and Output of Initial Propeller Input Data

```
****************************************************************************************************
                         PROPELLER-NACELLE AERODYNAMIC PERFORMANCE PROGRAM
                                        DEVELOPED BY
                              UNITED TECHNOLOGIES RESEARCH CENTER

                                        JANUARY 1979

                               FOR NASA LEWIS RESEARCH CENTER
                                   CONTRACT NAS3-20961

                          UTRC PROJECT MANAGER:  A. J. LANDGREBE (203-727-7358)
   COMPUTER PROGRAM DEVELOPERS: T. A. EGOLF, PRINCIPAL INVESTIGATOR (203-727-7188) - PROPELLER
                                O. L. ANDERSON, PRINCIPAL INVESTIGATOR (203-727-7224) - NACELLE
                                D. E. EDWARDS (203-727-7207) - NACELLE


                 NASA PROJECT MANAGER:  L. J. BOBER (216-433-4000 EXT. 5520)

                     THIS COMPUTER PROGRAM CALCULATES THE PROPELLER-NACELLE
                     FLOW FIELD, BLADE LOADING DISTRIBUTION, PROPELLER
                     PERFORMANCE, NACELLE PRESSURE AND VISCOUS DRAG.  THE
                     PROGRAM WAS DEVELOPED FOR APPLICATION TO HIGH-SPEED
                     PROPELLER (PROP-FAN) CONFIGURATIONS.  A PROPELLER
                     LIFTING LINE, PRESCRIBED WAKE MODULE AND AN AXISYM-
                     METRIC, COMPRESSIBLE, INVISCID OR VISCOUS NACELLE
                     MODULE CAN BE APPLIED INTERACTIVELY OR INDEPENDENTLY
                     TO SINGLE OR COAXIAL, COUNTER-ROTATING PROPELLERS WITH
                     SWEPT BLADES OPERATING WITH OR WITHOUT THE PRESENCE
                     OF A WIND TUNNEL WALL.  A DATA BANK OF ISOLATED AND
                     CASCADE AIRFOIL DATA FOR TYPICAL PROP-FAN AIRFOIL
                     SECTIONS IS INCLUDED.
****************************************************************************************************

     SWITCH NOPPF =   1
    FOR THIS MODE OF OPERATION,
           THE AERODYNAMIC CHARACTERISTICS OF A NACELLE AND
           PROPELLER ARE ANALYZED. (SPECIFICALLY, A.D.D. CODE
           AND PROPELLER LIFTING LINE CODE ARE OPERATED COUPLED
           SEQUENTIALLY).
************************************************************

           PRINTOUT OF INITIAL INPUT DATA AS READ IN
INPUT
STN         .11000000+02
DEBUG       .10000000+01
WAKEOP      .10000000+01
WAKNAC      .10000000+01
COMPRS      .10000000+01
CNSECT      .10000000+01
RDCAS1      .36700000+00
TYPESL      .00000000
EVA3RD      .10000000+01
VORCOR      .50000000-02
SKINOP      .10000000+01
STACK       .25000000+00
CASCAD      .10000000+01
ROLUP1      .00000000
TRUCT1      .00000000
TRUCI1      .00000000
SOLVEM      .00000000
CBWAKE      .00000000
COFLOW      .00000000
VKTAS       .52130000+03
RPM         .84400000+04
SOUND       .11110800+04
DENSTY      .18500000-02
```

```
BLADEN          .80000000+01
PROPNM          .10000000+01
RADI            .10268330+01
THETA1          .58509000+02
DCPDT           .30000000+00
DCTDT           .00000000
CPI             .16530000+01
CTI             .00000000
HUBQ1           .00000000
DPSI            .15000000+02
REV             .20000000+01
ZHUB            .00000000
BLADE
XSB
 .23920+00 .28570+00 .36730+00 .44900+00 .53060+00 .61220+00 .69390+00 .77550+00 .85710+00 .93880+00 .97960+00 .10000+01
ZSB
 .19105-01 .17982-01 .15686-01 .13321-01 .95130-02 .46230-02 .10330-02 .59760-04 .30470-02 .10756-01 .18116-01 .24321-01
YSB
 .55174-01 .56043-01 .58505-01 .63162-01 .62463-01 .49191-01 .27389-01-.34893-02-.42912-01-.89396-01-.12477+00-.15459+00
XMC
 .10000+01
ZMC
 .20450-01
YMC
-.12999+00
VARDAT
AIRN
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=   .23100+02   .23100+02    .23100+02    .23100+02    .23100+02    .23100+02    .23100+02    .23100+02    .23100+02    .23100+02
            .23100+02   .23100+02
THET
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=   .19099+02   .17789+02    .15009+02    .11908+02    .86590+01    .53690+01    .21590+01   -.98100+00   -.40610+01   -.68610+01
           -.82610+01  -.89410+01
DECL
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=  -.36700+00  -.26300+00   -.60000-01    .75000-01    .17000+00    .18800+00    .16000+00    .11500+00    .64000-01    .25000-01
            .10000-01   .80000-02
CORD
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=   .28630+00   .29030+00    .29800+00    .30040+00    .29770+00    .29260+00    .28910+00    .28290+00    .26970+00    .23570+00
            .18950+00   .10170+00
TOVC
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=   .21200+00   .11100+00    .70000-01    .45000-01    .40000-01    .33000-01    .28000-01    .25000-01    .22000-01    .21000-01
            .20500-01   .20000-01
DENS
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
            .97960+00   .10000+01
Y VECTOR=   .96760+00   .97300+00    .97860+00    .98270+00    .98490+00    .98650+00    .98810+00    .99030+00    .99160+00    .99350+00
            .99460+00   .99460+00
SOUN
12 INTERPOLATION STATIONS
X VECTOR=   .23920+00   .28570+00    .36730+00    .44900+00    .53060+00    .61220+00    .69390+00    .77550+00    .85710+00    .93880+00
```

```
              .97960+00     .10000+01
Y VECTOR=      .99390+00     .99460+00     .99560+00     .99650+00     .99720+00     .99780+00     .99810+00     .99830+00     .99850+00     .99900+00
              .99910+00     .99920+00
URVO
12 INTERPOLATION STATIONS
X VECTOR=      .23920+00     .28570+00     .36730+00     .44900+00     .53060+00     .61220+00     .69390+00     .77550+00     .85710+00     .93880+00
              .97960+00     .10000+01
Y VECTOR=      .38400+00     .35200+00     .30100+00     .25000+00     .21600+00     .18800+00     .16500+00     .14800+00     .13300+00     .11900+00
              .11400+00     .10900+00
VOVO
12 INTERPOLATION STATIONS
X VECTOR=      .23920+00     .28570+00     .36730+00     .44900+00     .53060+00     .61220+00     .69390+00     .77550+00     .85710+00     .93880+00
              .97960+00     .10000+01
Y VECTOR=      .96700+00     .97500+00     .98600+00     .99600+00     .99900+00     .10000+01     .10010+01     .10010+01     .10010+01     .10010+01
              .10010+01     .10010+01
```

## (2) Output of the Options and Input Data used in Nacelle Analysis

```
                 PROPFAN MODEL 1 BASELINE

CASE NO.  012979- 1
OPTIONS USED

          IOPT1 =  3    COMPUTE INLET FLOW
          IOPT2 =  3    CASCADE PREDICTED ZB AND ALPH2 FOR BLADE FORCE CALCULATION
          IOPT3 =  2    INPUT DUCT SHAPE AND WALL CONDITIONS
                        AT  81 MESH POINTS
          IOPT4 = -1    PRINT EVERY IOPT4 STATIONS
          IOPT5 =  0    UPSTREAM=INLET, DOWNSTREAM=EXIT
          IOPT9 =  3    READ 100 RECORDS ON FILE   0
                        SOLUTION NOT STORED ON TAPE LFILE=0
                       100 MESH POINTS INTERPOLATED FROM  81 INPUT POINTS
MESH PARAMETERS
          MESH DISTORTION PARAMETER                     DDS =  15296.556
          NUMBER OF MESH POINTS ACROSS DUCT             KL  =       45
          NUMBER OF MESH POINTS ALONG DUCT              JL  =      100
          NUMBER OF STEPS PER STATION                   KDS =        5
          MATCHING POINT                                KMO =        2
INLET FLOW PARAMETERS
          MS1 =        .7920                    DSH =     .0006 FT.              ANH =     10.00
          ALP1 =        .00 DEG.                DST =     .0010 FT.              ANT =     10.00
PERFORMANCE POINT
          WEIGHT FLOW                   WFLO  =    2446.59 LB/SEC
          REYNOLDS NUMBER               REY   =   .1672+08
          MEAN INLET DYNAMIC PRESSURE   DYNP1 =     834.36 PSF ABS.
          MEAN INLET MACH NUMBER        MACH1 =       .792
          MEAN INLET STATIC PRESSURE    PRES1 =    1628.36 PSF ABS.
          MEAN INLET STATIC TEMPERATURE ATEMP1=     512.66 DEG. R
          ROTOR SPEED                         =    8440.00  RPM
          AVERAGE INLET MACH NUMBER     MACHA=       .7340
          INLET REYNOLDS NUMBER          REYH=    .1713+08
          INLET BLOCKAGE FACTOR            B1=       .0281
REFERENCE CONDITIONS
          PRESR =    2117.00 PSF ABS.                USR   =    664.86 FT/SEC
          TEMPR =     519.00 DEG. RANKIN             RADR  =      3.91 FT
          RHOR  =     .00238 SLUGS/FT**3             SNDR  =   1116.05 FT/SEC
          CP    =    5997.00 FT**2/DEG.              CV    =   4283.00 FT**2/DEG.
          VISCR =    .370-06 SLUG/FT/SEC.            PR    =     .7200
TURBULENCE PARAMETERS
          AKAPPA =        .4000                 APLUS =        26.00
          ACHI   =        .0160                 PRT   =         .900

                 PROPFAN MODEL 1 BASELINE

  STRUT GEOMETRY
          STRUT CENTER LINE      ZCL    =    3.262 FT.
          NUMBER OF STRUTS       NBLADE =    8
          BLADE SHAPE            ISHAPE =    7
```

| RCL(FT.) | ALPS(DEG.) | CHORD(FT.) | THICK/CHORD | ZCLI(FT.) |
|---|---|---|---|---|
| .244 | 77.608 | .286 | .212 | 3.204 |
| .292 | 76.298 | .290 | .111 | 3.204 |
| .375 | 73.518 | .298 | .070 | 3.203 |
| .458 | 70.418 | .300 | .045 | 3.200 |
| .542 | 67.168 | .298 | .040 | 3.203 |
| .625 | 63.878 | .293 | .033 | 3.217 |
| .708 | 60.669 | .289 | .028 | 3.238 |
| .792 | 57.529 | .283 | .025 | 3.266 |
| .875 | 54.448 | .270 | .022 | 3.298 |
| .958 | 51.648 | .236 | .021 | 3.335 |
| 1.000 | 50.248 | .190 | .021 | 3.361 |
| 1.021 | 49.568 | .102 | .020 | 3.384 |

## (3) Output of the Nacelle Geometry

DUCT GEOMETRY AND WALL CONDITIONS

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| DUCTI( 1) = | 5.4167 | DUCTI( 2) = | 20.0000 | DUCTI( 3) = | .0000 | DUCTI( 4) = | .0000 | DUCTI( 5) = | .0000 |
| DUCTI( 6) = | .0000 | DUCTI( 7) = | .0000 | DUCTI( 8) = | .0000 | DUCTI( 9) = | .0000 | DUCTI(10) = | .0000 |
| DUCTI(11) = | .0000 | DUCTI(12) = | .0000 | DUCTI(13) = | .0000 | DUCTI(14) = | .0000 | DUCTI(15) = | .0000 |

| ZT | RT | MBT | TEMPT | ZH | RH | MBH | TEMPH |
|---|---|---|---|---|---|---|---|
| .00000 | .39088+01 | .00000 | .00000 | .00000 | .15352-01 | .00000 | .00000 |
| .54714-01 | .39088+01 | .00000 | .00000 | .54714-01 | .15930-01 | .00000 | .00000 |
| .10943+00 | .39088+01 | .00000 | .00000 | .10943+00 | .16508-01 | .00000 | .00000 |
| .16414+00 | .39088+01 | .00000 | .00000 | .16414+00 | .17086-01 | .00000 | .00000 |
| .21886+00 | .39088+01 | .00000 | .00000 | .21886+00 | .17663-01 | .00000 | .00000 |
| .27357+00 | .39088+01 | .00000 | .00000 | .27357+00 | .18238-01 | .00000 | .00000 |
| .32828+00 | .39088+01 | .00000 | .00000 | .32828+00 | .18813-01 | .00000 | .00000 |
| .38300+00 | .39088+01 | .00000 | .00000 | .38300+00 | .19387-01 | .00000 | .00000 |
| .43771+00 | .39088+01 | .00000 | .00000 | .43771+00 | .19961-01 | .00000 | .00000 |
| .49243+00 | .39088+01 | .00000 | .00000 | .49243+00 | .20536-01 | .00000 | .00000 |
| .54714+00 | .39088+01 | .00000 | .00000 | .54714+00 | .21113-01 | .00000 | .00000 |
| .60186+00 | .39088+01 | .00000 | .00000 | .60186+00 | .21692-01 | .00000 | .00000 |
| .65657+00 | .39088+01 | .00000 | .00000 | .65657+00 | .22272-01 | .00000 | .00000 |
| .71128+00 | .39088+01 | .00000 | .00000 | .71128+00 | .22854-01 | .00000 | .00000 |
| .76600+00 | .39088+01 | .00000 | .00000 | .76600+00 | .23436-01 | .00000 | .00000 |
| .82071+00 | .39088+01 | .00000 | .00000 | .82071+00 | .24018-01 | .00000 | .00000 |
| .87543+00 | .39088+01 | .00000 | .00000 | .87543+00 | .24597-01 | .00000 | .00000 |
| .93014+00 | .39088+01 | .00000 | .00000 | .93014+00 | .25173-01 | .00000 | .00000 |
| .98485+00 | .39088+01 | .00000 | .00000 | .98485+00 | .25744-01 | .00000 | .00000 |
| .10396+01 | .39088+01 | .00000 | .00000 | .10396+01 | .26312-01 | .00000 | .00000 |
| .10943+01 | .39088+01 | .00000 | .00000 | .10943+01 | .26879-01 | .00000 | .00000 |
| .11490+01 | .39088+01 | .00000 | .00000 | .11490+01 | .27448-01 | .00000 | .00000 |
| .12037+01 | .39088+01 | .00000 | .00000 | .12037+01 | .28023-01 | .00000 | .00000 |
| .12584+01 | .39088+01 | .00000 | .00000 | .12584+01 | .28606-01 | .00000 | .00000 |
| .13131+01 | .39088+01 | .00000 | .00000 | .13131+01 | .29196-01 | .00000 | .00000 |
| .13679+01 | .39088+01 | .00000 | .00000 | .13679+01 | .29792-01 | .00000 | .00000 |
| .14226+01 | .39088+01 | .00000 | .00000 | .14226+01 | .30386-01 | .00000 | .00000 |
| .14773+01 | .39088+01 | .00000 | .00000 | .14773+01 | .30973-01 | .00000 | .00000 |
| .15320+01 | .39088+01 | .00000 | .00000 | .15320+01 | .31546-01 | .00000 | .00000 |
| .15867+01 | .39088+01 | .00000 | .00000 | .15867+01 | .32103-01 | .00000 | .00000 |
| .16414+01 | .39088+01 | .00000 | .00000 | .16414+01 | .32648-01 | .00000 | .00000 |
| .16961+01 | .39088+01 | .00000 | .00000 | .16961+01 | .33191-01 | .00000 | .00000 |
| .17509+01 | .39088+01 | .00000 | .00000 | .17509+01 | .33742-01 | .00000 | .00000 |
| .18056+01 | .39088+01 | .00000 | .00000 | .18056+01 | .34314-01 | .00000 | .00000 |
| .18603+01 | .39088+01 | .00000 | .00000 | .18603+01 | .34913-01 | .00000 | .00000 |
| .19150+01 | .39088+01 | .00000 | .00000 | .19150+01 | .35538-01 | .00000 | .00000 |
| .19697+01 | .39088+01 | .00000 | .00000 | .19697+01 | .36178-01 | .00000 | .00000 |
| .20244+01 | .39088+01 | .00000 | .00000 | .20244+01 | .36809-01 | .00000 | .00000 |
| .20791+01 | .39088+01 | .00000 | .00000 | .20791+01 | .37411-01 | .00000 | .00000 |
| .21339+01 | .39088+01 | .00000 | .00000 | .21339+01 | .37965-01 | .00000 | .00000 |
| .21886+01 | .39088+01 | .00000 | .00000 | .21886+01 | .38471-01 | .00000 | .00000 |
| .22433+01 | .39088+01 | .00000 | .00000 | .22433+01 | .38948-01 | .00000 | .00000 |
| .22980+01 | .39088+01 | .00000 | .00000 | .22980+01 | .39440-01 | .00000 | .00000 |
| .23527+01 | .39088+01 | .00000 | .00000 | .23527+01 | .39999-01 | .00000 | .00000 |
| .24074+01 | .39088+01 | .00000 | .00000 | .24074+01 | .40655-01 | .00000 | .00000 |
| .24621+01 | .39088+01 | .00000 | .00000 | .24621+01 | .41374-01 | .00000 | .00000 |
| .25169+01 | .39088+01 | .00000 | .00000 | .25169+01 | .42033-01 | .00000 | .00000 |
| .25716+01 | .39088+01 | .00000 | .00000 | .25716+01 | .42391-01 | .00000 | .00000 |
| .26263+01 | .39088+01 | .00000 | .00000 | .26263+01 | .43776-01 | .00000 | .00000 |
| .26810+01 | .39088+01 | .00000 | .00000 | .26810+01 | .58067-01 | .00000 | .00000 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| .27357+01 | .39088+01 | .00000 | .00000 | .27357+01 | .91082-01 | .00000 | .00000 |
| .27904+01 | .39088+01 | .00000 | .00000 | .27904+01 | .11778+00 | .00000 | .00000 |
| .28451+01 | .39088+01 | .00000 | .00000 | .28451+01 | .13885+00 | .00000 | .00000 |
| .28998+01 | .39088+01 | .00000 | .00000 | .28998+01 | .15787+00 | .00000 | .00000 |
| .29546+01 | .39088+01 | .00000 | .00000 | .29546+01 | .17604+00 | .00000 | .00000 |
| .30093+01 | .39088+01 | .00000 | .00000 | .30093+01 | .19415+00 | .00000 | .00000 |
| .30640+01 | .39088+01 | .00000 | .00000 | .30640+01 | .21264+00 | .00000 | .00000 |
| .31187+01 | .39088+01 | .00000 | .00000 | .31187+01 | .23167+00 | .00000 | .00000 |
| .31734+01 | .39088+01 | .00000 | .00000 | .31734+01 | .25114+00 | .00000 | .00000 |
| .32281+01 | .39088+01 | .00000 | .00000 | .32281+01 | .27079+00 | .00000 | .00000 |
| .32828+01 | .39088+01 | .00000 | .00000 | .32828+01 | .29018+00 | .00000 | .00000 |
| .33376+01 | .39088+01 | .00000 | .00000 | .33376+01 | .30882+00 | .00000 | .00000 |
| .33923+01 | .39088+01 | .00000 | .00000 | .33923+01 | .32617+00 | .00000 | .00000 |
| .34470+01 | .39088+01 | .00000 | .00000 | .34470+01 | .34170+00 | .00000 | .00000 |
| .35017+01 | .39088+01 | .00000 | .00000 | .35017+01 | .35494+00 | .00000 | .00000 |
| .35564+01 | .39088+01 | .00000 | .00000 | .35564+01 | .36555+00 | .00000 | .00000 |
| .36111+01 | .39088+01 | .00000 | .00000 | .36111+01 | .37335+00 | .00000 | .00000 |
| .36658+01 | .39088+01 | .00000 | .00000 | .36658+01 | .37839+00 | .00000 | .00000 |
| .37206+01 | .39088+01 | .00000 | .00000 | .37206+01 | .38094+00 | .00000 | .00000 |
| .37753+01 | .39088+01 | .00000 | .00000 | .37753+01 | .38148+00 | .00000 | .00000 |
| .38300+01 | .39088+01 | .00000 | .00000 | .38300+01 | .38046+00 | .00000 | .00000 |
| .38847+01 | .39088+01 | .00000 | .00000 | .38847+01 | .37824+00 | .00000 | .00000 |
| .39394+01 | .39088+01 | .00000 | .00000 | .39394+01 | .37508+00 | .00000 | .00000 |
| .39941+01 | .39088+01 | .00000 | .00000 | .39941+01 | .37119+00 | .00000 | .00000 |
| .40488+01 | .39088+01 | .00000 | .00000 | .40488+01 | .36671+00 | .00000 | .00000 |
| .41036+01 | .39088+01 | .00000 | .00000 | .41036+01 | .36176+00 | .00000 | .00000 |
| .41583+01 | .39088+01 | .00000 | .00000 | .41583+01 | .35646+00 | .00000 | .00000 |
| .42130+01 | .39088+01 | .00000 | .00000 | .42130+01 | .35094+00 | .00000 | .00000 |
| .42677+01 | .39088+01 | .00000 | .00000 | .42677+01 | .34538+00 | .00000 | .00000 |
| .43224+01 | .39088+01 | .00000 | .00000 | .43224+01 | .33999+00 | .00000 | .00000 |
| .43771+01 | .39088+01 | .00000 | .00000 | .43771+01 | .33504+00 | .00000 | .00000 |
| .44318+01 | .39088+01 | .00000 | .00000 | .44318+01 | .33082+00 | .00000 | .00000 |
| .44866+01 | .39088+01 | .00000 | .00000 | .44866+01 | .32757+00 | .00000 | .00000 |
| .45413+01 | .39088+01 | .00000 | .00000 | .45413+01 | .32549+00 | .00000 | .00000 |
| .45960+01 | .39088+01 | .00000 | .00000 | .45960+01 | .32468+00 | .00000 | .00000 |
| .46507+01 | .39088+01 | .00000 | .00000 | .46507+01 | .32513+00 | .00000 | .00000 |
| .47054+01 | .39088+01 | .00000 | .00000 | .47054+01 | .32665+00 | .00000 | .00000 |
| .47601+01 | .39088+01 | .00000 | .00000 | .47601+01 | .32887+00 | .00000 | .00000 |
| .48148+01 | .39088+01 | .00000 | .00000 | .48148+01 | .33133+00 | .00000 | .00000 |
| .48696+01 | .39088+01 | .00000 | .00000 | .48696+01 | .33373+00 | .00000 | .00000 |
| .49243+01 | .39088+01 | .00000 | .00000 | .49243+01 | .33603+00 | .00000 | .00000 |
| .49790+01 | .39088+01 | .00000 | .00000 | .49790+01 | .33832+00 | .00000 | .00000 |
| .50337+01 | .39088+01 | .00000 | .00000 | .50337+01 | .34062+00 | .00000 | .00000 |
| .50884+01 | .39088+01 | .00000 | .00000 | .50884+01 | .34296+00 | .00000 | .00000 |
| .51431+01 | .39088+01 | .00000 | .00000 | .51431+01 | .34533+00 | .00000 | .00000 |
| .51978+01 | .39088+01 | .00000 | .00000 | .51978+01 | .34772+00 | .00000 | .00000 |
| .52526+01 | .39088+01 | .00000 | .00000 | .52526+01 | .35011+00 | .00000 | .00000 |
| .53073+01 | .39088+01 | .00000 | .00000 | .53073+01 | .35247+00 | .00000 | .00000 |
| .53620+01 | .39088+01 | .00000 | .00000 | .53620+01 | .35480+00 | .00000 | .00000 |
| .54167+01 | .39088+01 | .00000 | .00000 | .54167+01 | .35713+00 | .00000 | .00000 |

UPSTREAM STATION = 49 DOWNSTREAM STATION = 59

BEGIN INVISCID FLOW CALCULATION
TIME 0 77.28840

(4) Output of the Inviscid Flow Solution (At Axial Station ZH = .76489)



GAP AVERAGE INVISCID FLOW

JJ= 50 ZH= .76489 ZT= .70159 RH= .04532 RT= 1.00000

| Y | PT | P | ALP | TT |
|---|---|---|---|---|
| .00000 | 2462.72000 | 1690.57368 | .00000 | 577.00000 |
| .07143 | 2462.72000 | 1673.01753 | .00000 | 577.00000 |
| .14286 | 2462.72000 | 1655.75549 | .00000 | 577.00000 |
| .21429 | 2462.72000 | 1644.56288 | .00000 | 577.00000 |
| .28571 | 2462.72000 | 1638.07289 | .00000 | 577.00000 |
| .35714 | 2462.72000 | 1633.78140 | .00000 | 577.00000 |
| .42857 | 2462.72000 | 1632.21742 | .00000 | 577.00000 |
| .50000 | 2462.72000 | 1630.74451 | .00000 | 577.00000 |
| .57143 | 2462.72000 | 1630.10506 | .00000 | 577.00000 |
| .64286 | 2462.72000 | 1629.47581 | .00000 | 577.00000 |
| .71429 | 2462.72000 | 1629.10779 | .00000 | 577.00000 |
| .78571 | 2462.72000 | 1628.78183 | .00000 | 577.00000 |
| .85714 | 2462.72000 | 1628.55367 | .00000 | 577.00000 |
| .92857 | 2462.72000 | 1628.42165 | .00000 | 577.00000 |
| 1.00000 | 2462.72000 | 1628.35915 | .00000 | 577.00000 |

INVISCID PRESSURE COEF. ON WALL = .87002-01

| Y | MACH | TEMP | VEL | VELS | VELP | UZ | UR | C | RHO |
|---|---|---|---|---|---|---|---|---|---|
| .17715 | .75320 | 518.17921 | 839.93848 | 839.93848 | .00000 | 797.40154 | 263.90769 | 1115.16309 | .00190 |
| .44369 | .76416 | 516.63549 | 850.88895 | 850.88895 | .00000 | 828.00293 | 194.38176 | 1113.50075 | .00189 |
| .71024 | .77492 | 515.10631 | 861.59911 | 861.59911 | .00000 | 850.59202 | 135.91215 | 1111.85161 | .00188 |
| .97679 | .78190 | 514.10870 | 868.51500 | 868.51500 | .00000 | 862.38361 | 100.98738 | 1110.77441 | .00187 |
| 1.24333 | .78595 | 513.52802 | 872.51535 | 872.51535 | .00000 | 868.91374 | 77.59070 | 1110.14694 | .00186 |
| 1.50988 | .78862 | 513.14314 | 875.15672 | 875.15672 | .00000 | 873.11853 | 59.41539 | 1109.73083 | .00186 |
| 1.77643 | .78960 | 513.00269 | 876.11855 | 876.11855 | .00000 | 874.69552 | 48.76025 | 1109.57896 | .00186 |
| 2.04297 | .79051 | 512.87034 | 877.02405 | 877.02405 | .00000 | 876.18514 | 38.31864 | 1109.43582 | .00186 |
| 2.30952 | .79091 | 512.81285 | 877.41707 | 877.41707 | .00000 | 876.82682 | 31.42638 | 1109.37364 | .00185 |
| 2.57607 | .79130 | 512.75627 | 877.80369 | 877.80369 | .00000 | 877.45805 | 24.56722 | 1109.31244 | .00185 |
| 2.84261 | .79153 | 512.72317 | 878.02984 | 878.02984 | .00000 | 877.80830 | 19.13971 | 1109.27663 | .00185 |
| 3.10916 | .79174 | 512.69385 | 878.23008 | 878.23008 | .00000 | 878.11514 | 13.89547 | 1109.24492 | .00185 |
| 3.37571 | .79188 | 512.67332 | 878.37022 | 878.37022 | .00000 | 878.32170 | 9.07613 | 1109.22270 | .00185 |
| 3.64225 | .79196 | 512.66144 | 878.45132 | 878.45132 | .00000 | 878.43851 | 4.49054 | 1109.20985 | .00185 |
| 3.90880 | .79200 | 512.65582 | 878.48974 | 878.48974 | .00000 | 878.48969 | .00008 | 1109.20377 | .00185 |

SOLUTION CONVERGED IWFLOW= 0 ERRW= .00000 ITERAL= 1 ERRAM= .00000

## (5) Output of the Lifting Line Noninduced Inflow Conditions



LOCATION OF LIFTING LINE

| RL | ZL | NL | SL |
|---|---|---|---|
| .64466-01 | .81976+00 | .00000 | .76324+00 |
| .74614-01 | .81972+00 | .32193+00 | .76660+00 |
| .95925-01 | .81949+00 | .36741+00 | .79390+00 |
| .11726+00 | .81877+00 | .38954+00 | .79947+00 |
| .13857+00 | .81945+00 | .40435+00 | .80387+00 |
| .15988+00 | .82307+00 | .41483+00 | .81360+00 |
| .19122+00 | .82841+00 | .42369+00 | .82131+00 |
| .20253+00 | .83542+00 | .43214+00 | .83454+00 |
| .22384+00 | .84380+00 | .43786+00 | .84577+00 |
| .24518+00 | .85310+00 | .44361+00 | .85837+00 |
| .25584+00 | .85997+00 | .44650+00 | .86497+00 |
| .26116+00 | .86576+00 | .44794+00 | .86827+00 |

UPSTREAM STATION = 49 DOWNSTREAM STATION = 59

LIFTING LINE FLOW CONDITIONS

| URL | UZL | RHOL | SNDL | COST | SINT |
|---|---|---|---|---|---|
| .31919+03 | .90043+03 | .17489-02 | .10964+04 | .94253+00 | .33412+00 |
| .29924+03 | .90206+03 | .17550-02 | .10972+04 | .94861+00 | .31468+00 |
| .25814+03 | .90486+03 | .17679-02 | .10988+04 | .96102+00 | .27417+00 |
| .21910+03 | .92462+03 | .17557-02 | .10973+04 | .97286+00 | .23053+00 |
| .18895+03 | .91665+03 | .17728-02 | .10994+04 | .97934+00 | .20143+00 |
| .16222+03 | .92603+03 | .17698-02 | .10990+04 | .98493+00 | .17254+00 |
| .14395+03 | .91887+03 | .17836-02 | .11007+04 | .98787+00 | .15475+00 |
| .12265+03 | .91933+03 | .17873-02 | .11012+04 | .99123+00 | .13225+00 |
| .10781+03 | .92670+03 | .17880-02 | .11013+04 | .99331+00 | .11631+00 |
| .94019+02 | .91965+03 | .17916-02 | .11017+04 | .99502+00 | .10172+00 |
| .89929+02 | .91632+03 | .17967-02 | .11023+04 | .99540+00 | .97689-01 |
| .87905+02 | .91464+03 | .17992-02 | .11026+04 | .99558+00 | .95684-01 |

(6) Output of the Options and Reference Data used in Propeller Analysis

```
*******************************************************************************
* UNITED TECHNOLOGIES RESEARCH CENTER :  PRESCRIBED WAKE PROP-FAN PROGRAM     *
*******************************************************************************
```

PROGRAM INPUT SUMMARY

PROPELLER MODELING OPTIONS

```
 1 SKEWED FLOW SKIN FRICTION DRAG ADDITION
 1 COMPRESSIBLE WAKE EFFECTS USED
 1 MACH CONE(TABLE FORM) CORRECTION USED
 0 NON LINEAR SOLUTION USED
 0 DIRECT SOLUTION TECHNIQUE USED
 0 NO COMPRESSIBILITY CORRECTION ON BOUND VORTEX
 0 COMPRESSIBLE WAKE APPLIED ONLY FOR SEGMENT MACH>1
 1 UNIFORM WAKE MODEL USED(VO+VIMOM)
 1 NACELLE EFFECTS ON WAKE USED
 1 HSD CASCADE CORRECTION USED ON ISOLATED AIRFOIL    DATA
 1 CASCADE AIRFOIL DATA PACKAGE USED INBOARD OF .367 R
```

NO WAKE ROLLUP FOR PROPELLER 1

FREE STREAM CONDITIONS:

```
V=  520.4321 KNOTS          SPEED OF SOUND = 1109.2038 FPS          DENSITY =  .0018532 SLUGS/CU FT
COMMON PROPELLER OPERATING CHARACTERISTICS:

NO. OF PROPELLERS =  1  NO. OF BLADES =   8.  RPM=   8440.00  AXIAL DISPLACEMENT BETWEEN PROPELLERS=    .00000 (NDN)
BLADE AND WAKE GEOMETRY OPERATING PARAMETERS:

NO. OF INFLOW STA.S=  11.  POS. OF LIFTING LINE W.R.T. LEAD. EDGE= .250 (NDN)  AZI. INCREMENT=15.00 DEG.  NO. OF WAKE REVS= 2.
PERCENT CHORD FOR MACH CONE INTERSECTION TEST = 100.0000
                         PROPELLER CHARACTERISTICS FOR PROPELLER 1
BLADE RADIUS=  1.021 FT     HUB TORQUE=    .000 FT-LBS  INITIAL COLLECTIVE=  58.51 DEG.  END CASCADE REGION=.3670 (NDN)
VIMOM= -25.79 FPS
```

BLADE SEGMENT BOUNDARY COORDINATES

| BOUNDARY NO. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| X/RADIUS | .239[illegible] | .2857 | .3673 | .4490 | .5306 | .6122 | .6939 | .7755 | .8571 | .9388 | .9796 | 1.0000 |
| Y/RADIUS | .0552 | .0560 | .0585 | .0632 | .0625 | .0492 | .0274 | -.0035 | -.0429 | -.0894 | -.1248 | -.1546 |
| Z/RADIUS | .0191 | .0180 | .0157 | .0133 | .0095 | .0046 | .0010 | .0001 | .0030 | .0108 | .0181 | .0243 |

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| BLADE STATIONS | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FOR INFLOW SOLN. | .2624 | .3265 | .4081 | .4898 | .5714 | .6530 | .7347 | .8163 | .8980 | .9592 | .9698 |
| BLADE CHORD (FT) | .2883 | .2944 | .2995 | .2995 | .2952 | .2909 | .2866 | .2760 | .2589 | .2246 | .1510 |
| PITCH INCREMENT | 18.469 | 16.457 | 13.488 | 10.296 | 7.011 | 3.755 | .581 | -2.542 | -5.478 | -7.564 | -8.603 |
| THICKNESS RATIO | .154 | .079 | .055 | .041 | .036 | .030 | .026 | .023 | .021 | .021 | .020 |
| AIRFOIL SERIES NO. | 23. | 23. | 23. | 23. | 23. | 23. | 23. | 23. | 23. | 23. | 23. |
| DESIGN CL | -.316 | -.159 | .014 | .130 | .187 | .178 | .139 | .089 | .043 | .016 | .009 |
| VA / VO | 1.0259 | 1.0272 | 1.0419 | 1.0500 | 1.0500 | 1.0505 | 1.0456 | 1.0474 | 1.0482 | 1.0451 | 1.0421 |
| VR / VO | .3523 | .3176 | .2708 | .2314 | .1990 | .1739 | .1515 | .1306 | .1143 | .1046 | .1012 |
| SECTION ADVANCE RATIO | 3.1378 | 3.1418 | 3.1866 | 3.2114 | 3.2114 | 3.2131 | 3.1980 | 3.2034 | 3.2058 | 3.1964 | 3.1873 |
| SECTION INFLOW MACH # | .8216 | .8216 | .8335 | .8398 | .8390 | .8390 | .8342 | .8354 | .8359 | .8330 | .8303 |
| DENSITY RATIO | .9453 | .9513 | .9506 | .9517 | .9559 | .9585 | .9639 | .9646 | .9654 | .9681 | .9702 |
| SPEED OF SOUND RATIO | .9888 | .9900 | .9899 | .9901 | .9910 | .9915 | .9927 | .9928 | .9930 | .9935 | .9940 |

TIME TO COMPUTE INITIAL DATA IS .37 SEC

PROGRAM OUTPUT FOR PROPELLER PERFORMANCE ITERATION NUMBER 1

TABLE OF BLADE GEOMETRY QUANTITIES FOR THETAO OF 58.50900 DEGREES FOR PROPELLER 1

| SEGMENT CENTERS | | | | | | SEGMENT BOUNDARIES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SPAN POSITION/R | AXIAL DISP. | LAG DISP. | ACTUAL RADIUS/R | LAG ANGLE(DEG) | DROOP ANGLE(DEG) | SPAN POSITION/R | AXIAL DISP. | LAG DISP. | ACTUAL RADIUS/R | LAG ANGLE(DEG) | DROOP ANGLE(DEG) |
| .2624 | .0571 | .0132 | .2628 | 2.8870 | 12.2753 | .2392 | .0570 | .0125 | .2395 | 2.9985 | 12.2753 |
| .3265 | .0576 | .0156 | .3269 | 2.7290 | 10.0105 | .2857 | .0572 | .0139 | .2860 | 2.7936 | 10.0105 |
| .4081 | .0595 | .0194 | .4086 | 2.7227 | 8.2873 | .3673 | .0581 | .0172 | .3677 | 2.6788 | 8.2873 |
| .4898 | .0595 | .0231 | .4903 | 2.6973 | 6.9292 | .4490 | .0608 | .0216 | .4495 | 2.7586 | 6.9292 |
| .5714 | .0513 | .0231 | .5719 | 2.3185 | 5.1299 | .5306 | .0582 | .0245 | .5312 | 2.6455 | 5.1299 |
| .6530 | .0341 | .0176 | .6533 | 1.5429 | 2.9915 | .6122 | .0444 | .0218 | .6126 | 2.0351 | 2.9915 |
| .7347 | .0105 | .0058 | .7347 | .4505 | .8169 | .6939 | .0239 | .0134 | .6940 | 1.1085 | .8169 |
| .8163 | -.0190 | -.0134 | .8164 | -.9435 | -1.3314 | .7755 | -.0029 | -.0019 | .7755 | -.1384 | -1.3314 |
| .8980 | -.0528 | -.0404 | .8989 | -2.5787 | -3.3655 | .8571 | -.0350 | -.0250 | .8575 | -1.6717 | -3.3655 |
| .9592 | -.0838 | -.0682 | .9616 | -4.0697 | -4.9913 | .9388 | -.0706 | -.0559 | .9405 | -3.4057 | -4.9913 |
| .9898 | -.1080 | -.0911 | .9940 | -5.2562 | -6.2285 | .9796 | -.0969 | -.0806 | .9829 | -4.7051 | -6.2285 |
| | | | | | | 1.0000 | -.1191 | -.1015 | 1.0051 | -5.7951 | -6.7928 |

(7) Output of Selected Intermediate Calculation Results for the Propeller Analysis

```
        X,Y,Z FOR MACH CONE DEFINITION=         1.00000        -.08534        -.10016

                                         DETAILED BLADE ELEMENT OUTPUT
IP=  1
SB     =  .0465   .0817   .0819   .0817   .0828   .0846   .0873   .0907   .0943   .0545   .0367   .0000   .0000   .0000   .0000
ALSRAD=   .9998   .9999   .9994   .9994   .9831   .9623   .9337   .9039   .8799   .7789   .6063   .0000   .0000   .0000   .0000
ALSPHI=  -.0202  -.0080   .0070  -.0118  -.0736  -.1248  -.1833  -.2410  -.2885  -.4001  -.5159   .0000   .0000   .0000   .0000
ALSAXL=   .0033   .0110   .0334  -.0316  -.1675  -.2418  -.3076  -.3535  -.3776  -.4830  -.6052   .0000   .0000   .0000   .0000
CINFUT=   .2883   .2944   .2999   .2995   .2952   .2909   .2866   .2780   .2589   .2246   .1510   .0000   .0000   .0000   .0000
ALCIRD=   .0113   .0124   .0147   .0170   .0168   .0125   .0040  -.0092  -.0271  -.0447  -.0590   .0000   .0000   .0000   .0000
ALCIPH=   .2250   .2591   .3087   .3612   .4140   .4652   .5137   .5596   .6008   .6285   .6413   .0000   .0000   .0000   .0000
ALCIAX=   .9743   .9658   .9510   .9324   .9101   .8851   .8580   .8287   .7990   .7765   .7650   .0000   .0000   .0000   .0000
ALNRAD=  -.0204  -.0106  -.0037   .0004   .0024   .0021   .0008  -.0021  -.0042  -.0096  -.0118   .0000   .0000   .0000   .0000
ALNPHI=  -.9741  -.9658  -.9511  -.9325  -.9103  -.8852  -.8580  -.6288  -.7993  -.7776  -.7667   .0000   .0000   .0000   .0000
ALNAXL=   .2252   .2592   .3088   .3612   .4141   .4652   .5137   .5596   .6009   .6287   .6419   .0000   .0000   .0000   .0000
CHORD  =  .2824   .2684   .2934   .2934   .2851   .2752   .2625   .2451   .2198   .1650   .0826   .0000   .0000   .0000   .0000


ALCRAD=   .0013  -.0086  -.0339   .0338   .1829   .2721   .3581   .4278   .4751   .6271   .7952   .0000   .0000   .0000   .0000
ALCPHI=   .2253   .2593   .3057   .3610   .4075   .4462   .4799   .5051   .5272   .4851   .3820   .0000   .0000   .0000   .0000
ALCAXL=   .9743   .9658   .9565   .9320   .8947   .8515   .8009   .7496   .7045   .6094   .4709   .0000   .0000   .0000   .0000
TOVERC=   .1545   .0797   .0552   .0414   .0365   .0302   .0264   .0234   .0214   .0208   .0203   .0000   .0000   .0000   .0000
ALTIRD=  -.0491  -.0460  -.0452  -.0439  -.0368  -.0238  -.0067   .0136   .0359   .0551   .0701   .0000   .0000   .0000   .0000
ALTIPH=  -.9730  -.9647  -.9500  -.9313  -.9094  -.8848  -.8579  -.8286  -.7981  -.7746  -.7618   .0000   .0000   .0000   .0000
ALTIAX=   .2253   .2594   .3091   .3616   .4144   .4654   .5137   .5597   .6014   .6301   .6440   .0000   .0000   .0000   .0000
THK    =  .15440  .07862  .05526  .04134  .03699  .03132  .02820  .02597  .02464  .02766  .03618  .00000  .00000  .00000  .00000
DESCLP=  -.31608 -.15891  .01428  .12982  .18932  .18429  .14858  .09904  .04961  .02186  .01530  .00000  .00000  .00000  .00000

                         DETAILED VELOCITY RELATED OUTPUT(EXCLUDING INDUCED  VELOCITY TERMS
L=  1 IP=  1
VTOT   =  981.869 989.4361014.9271042.9131071.1841105.5591140.4911184.1321231.0411266.4641284.562   .000    .000    .000    .000
ALVRAD=   .3152   .2620   .2344   .1949   .1632   .1381   .1167   .0969   .0815   .0725   .0692   .0000   .0000   .0000   .0000
ALVPHI=  -.2415  -.2981  -.3632  -.4242  -.4817  -.5331  -.5812  -.6221  -.6588  -.6851  -.6982   .0000   .0000   .0000   .0000
ALVAXL=  -.9178  -.9119  -.9017  -.8843  -.8610  -.8347  -.8053  -.7769  -.7479  -.7249  -.7126   .0000   .0000   .0000   .0000
ALPHAN=   .0233   .0504   .0676   .0764   .0877   .0917   .0962   .0939   .0917   .1043   .1399   .0000   .0000   .0000   .0000
SKEW   =  18.4849 15.9401 11.6573 13.2050 19.9538 23.7496 27.7017 30.9191 33.0780 43.0535 56.7081 .0000   .0000   .0000   .0000
VS     =  .3170   .2743   .2016   .2278   .3401   .4013   .4632   .5122   .5442   .6807   .8334   .0000   .0000   .0000   .0000
VC     = -.9482  -.9604  -.9772  -.9707  -.9368  -.9121  -.8822  -.6551  -.8355  -.7286  -.5473   .0000   .0000   .0000   .0000
VN     =  .0221   .0485   .0662   .0762   .0823   .0839   .0851   .0806   .0768   .0762   .0771   .0000   .0000   .0000   .0000
TIME TO CAL. RELATIVE GEOMETRY ETC. IS     .00000 SEC
                                           PROPELLER 1

                     AXIAL WAKE TRANSPORT VELOCITY USED AT PROPELLER DISK (NEGLECTING NACELLE INFLUENCE)
RSB     .240     .286     .368     .450     .531     .613     .694     .776     .857     .940     .983    1.005
VT   -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18  -904.18
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(8) Output of the Propeller Performance Results

••• PROPELLER PERFORMANCE •••

BLADE SPANWISE VARYING QUANTITIES

ROTOR POSITION 1 PROPELLER 1

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SEGMENT NUMBER | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| X-WISE LOCATION /BLADE RADIUS | X | .263 | .327 | .409 | .490 | .572 | .653 | .735 | .816 | .899 | .962 |
| CHORD/RADIUS (BLADE ELEMENT) | CHORD | .282 | .288 | .293 | .293 | .285 | .275 | .263 | .245 | .220 | .165 |
| CHORD(INPUT),FT. | CINPUT | .288 | .294 | .300 | .300 | .295 | .291 | .287 | .278 | .259 | .225 |
| THICKNESS RATIO (INPUT) | TOVERC | .1545 | .0787 | .0552 | .0414 | .0365 | .0302 | .0264 | .0234 | .0214 | .0208 |
| THICKNESS RATIO (BLADE ELEMENT) | THK | .1544 | .0786 | .0553 | .0413 | .0370 | .0313 | .0282 | .0260 | .0246 | .0277 |
| DESIGN LIFT COEF (INPUT), | DESCL | -.31606 | -.15887 | .01426 | .12980 | .18668 | .17794 | .13894 | .08912 | .04300 | .01640 |
| DESIGN LIFT COEF(BLADE ELEMENT), | DESCLP | -.31608 | -.15891 | .01426 | .12982 | .18932 | .18428 | .14857 | .09904 | .04961 | .02186 |
| SECTION CASCADE SOLIDITY | SIGMAX | 1.368 | 1.123 | .914 | .762 | .635 | .536 | .455 | .382 | .311 | .219 |
| GEO. ANG. BETWEEN C AND PHI(DEG) | THETAG | 77.810 | 75.799 | 72.848 | 69.662 | 66.750 | 64.148 | 62.075 | 60.393 | 58.901 | 61.612 |
| BLADE ELEMENT BLADE ANGLE, DEG. | THETAB | 2.22 | 3.75 | 4.72 | 5.34 | 5.90 | 6.15 | 6.44 | 6.34 | 6.24 | 7.10 |
| SEGMENT LENGTH/R(BLADE ELEMENT) | DS | .047 | .082 | .082 | .082 | .083 | .085 | .087 | .091 | .094 | .055 |
| SECTION LENGTH / BLADE RADIUS | DX | .047 | .082 | .082 | .082 | .082 | .082 | .082 | .082 | .082 | .041 |
| AXIAL INDUCED VELOCITY, FPS | UIZ | -145.134 | -115.887 | -92.364 | -89.601 | -19.260 | 20.264 | 6.229 | 2.021 | -.739 | -11.372 |
| TANGENTIAL INDUCED VELOCITY,FPS | UIT | -16.889 | 9.852 | 27.663 | 31.018 | 60.927 | 80.732 | 69.678 | 62.272 | 57.368 | 64.272 |
| RADIAL INDUCED VELOCITY, FPS | UIR | -40.198 | -50.089 | -55.645 | -50.637 | -34.831 | -11.599 | -8.107 | -6.445 | -5.567 | -6.739 |
| NORMAL INDUCED VELOCITY, FPS | VIN | -11.478 | -37.557 | -53.768 | -60.327 | -63.656 | -62.860 | -57.180 | -50.986 | -46.759 | -57.507 |
| CHORDWISE INDUCED VELOCITY, FPS | VIC | -145.848 | -109.429 | -78.020 | -74.831 | .369 | 49.441 | 34.763 | 29.535 | 26.456 | 19.321 |
| SPANWISE INDUCED VELOCITY, FPS | VIS | -40.414 | -51.483 | -56.530 | -48.119 | -35.271 | -25.826 | -21.946 | -21.250 | -20.889 | -25.006 |
| TOTAL NORMAL VELOCITY, FPS | VN | 24.53 | 24.72 | 28.00 | 34.14 | 39.90 | 45.72 | 56.23 | 61.36 | 65.42 | 57.09 |
| TOTAL CHORDWISE VELOCITY,FPS | VC | -1076.75 | -1059.21 | -1069.00 | -1086.25 | -1002.14 | -957.86 | -970.04 | -981.42 | -999.96 | -900.68 |
| TOTAL SPANWISE VELOCITY,FPS | VS | 269.70 | 218.70 | 144.77 | 187.98 | 327.58 | 416.67 | 505.52 | 584.99 | 649.41 | 837.69 |
| INPUT RADIAL VELOCITY,FPS | UR | 309.50 | 279.02 | 237.91 | 203.23 | 174.82 | 152.72 | 133.07 | 114.75 | 100.37 | 91.84 |
| INPUT TANGENTIAL VELOCITY,FPS | UT | 237.06 | 294.88 | 368.63 | 442.38 | 515.94 | 589.42 | 662.90 | 736.60 | 810.97 | 867.55 |
| INPUT AXIAL VELOCITY,FPS | UZ | 901.15 | 902.31 | 915.18 | 922.30 | 922.31 | 922.77 | 918.46 | 920.01 | 920.69 | 918.00 |
| RESULTANT VELOCITY, FPS | VTT | 1110.29 | 1081.83 | 1079.12 | 1102.92 | 1055.07 | 1045.56 | 1095.31 | 1144.18 | 1194.12 | 1231.35 |
| SKEW ANGLE(BLADE ELEMENT),DEG | SKEW | 14.06 | 11.67 | 7.71 | 9.82 | 18.10 | 23.51 | 27.53 | 30.80 | 33.00 | 42.92 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CIRCULATION, FT SQ/SEC. | GAMMA | -1.57 | 6.71 | 18.13 | 29.55 | 53.77 | 68.50 | 83.02 | 87.26 | 59.63 | 23.16 |
| BLADE ELEMENT INFLOW ANGLE,DEG. | PHI | -.910 | -2.414 | -3.217 | -3.536 | -3.618 | -3.420 | -3.122 | -2.764 | -2.494 | -3.474 |
| BL. ELEMENT ANG. OF ATTACK, DEG. | ALPHA | 1.305 | 1.337 | 1.501 | 1.800 | 2.280 | 2.733 | 3.317 | 3.577 | 3.743 | 3.627 |
| MACH NUMBER | CMACH | 1.0123 | .9851 | .9828 | 1.0042 | .9598 | .9507 | .9948 | 1.0390 | 1.0842 | 1.1174 |
| BLADE ELEMENT MACH NUMBER | SMACH | .9620 | .9648 | .9739 | .9895 | .9124 | .8719 | .8825 | .8929 | .9098 | .8190 |
| SECTION SPEED OF SOUND RATIO | SOUN | .98881 | .99005 | .98990 | .99014 | .99102 | .99154 | .99266 | .99282 | .99297 | .99352 |
| SECTION DENSTY RATIO | DENS | .94530 | .95125 | .95056 | .95170 | .95593 | .95851 | .96389 | .96465 | .96544 | .96809 |
| TIP MACH CONE CORRECTION | K-CONE | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | .695 | .537 |
| LIFT COEF. (BLADE ELEMENT) | CL | -.0101 | .0431 | .1132 | .1816 | .3684 | .5086 | .6376 | .7094 | .5304 | .3046 |
| DRAG COEF. (BLADE ELEMENT) | CD | .0075 | .0061 | .0250 | .0207 | .0187 | .0257 | .0453 | .0638 | .0689 | .0298 |
| MIN. DRAG COEF. (BLADE ELEMENT) | CD | .0072 | .0059 | .0234 | .0178 | .0116 | .0084 | .0074 | .0062 | .0060 | .0053 |
| THRUST COEFFICIENT GRADIENT | DCT/DX | -.0372 | .0206 | .0484 | .1957 | .4822 | .6930 | .9649 | 1.1485 | .8578 | .3745 |
| POWER COEFFICIENT GRADIENT | DCP/DX | -.0248 | .1655 | .5727 | 1.0848 | 2.0592 | 2.8474 | 3.9913 | 4.7944 | 3.7946 | 1.5834 |

ORIGINAL PAGE IS
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BLADE SPANWISE VARYING QUANTITIES

ROTOR POSITION 1 PROPELLER 1

| | | |
|---|---|---|
| SEGMENT NUMBER | | 11 |
| X-WISE LOCATION /BLADE RADIUS | X | .994 |
| CHORD/RADIUS (BLADE ELEMENT) | CHORD | .083 |
| CHORD(INPUT),FT. | CINPUT | .151 |
| THICKNESS RATIO (INPUT) | TOVERC | .0203 |
| THICKNESS RATIO (BLADE ELEMENT) | THK | .0362 |
| DESIGN LIFT COEF(INPUT), | DESCL | .00854 |
| DESIGN LIFT COEF(BLADE ELEMENT), | DESCLP | .01530 |
| SECTION CASCADE SOLIDITY | SIGMAX | .106 |
| GEO. ANG. BETWEEN C AND PHI(DEG) | THETAG | 68.039 |
| BLADE ELEMENT BLADE ANGLE, DEG. | THETAB | 9.51 |
| SEGMENT LENGTH/R(BLADE ELEMENT) | DS | .037 |
| SECTION LENGTH / BLADE RADIUS | DX | .020 |
| AXIAL INDUCED VELOCITY, FPS | UIZ | -9.965 |
| TANGENTIAL INDUCED VELOCITY,FPS | UIT | 62.540 |
| RADIAL INDUCED VELOCITY, FPS | UIR | -6.270 |
| NORMAL INDUCED VELOCITY, FPS | VIN | -54.732 |
| CHORDWISE INDUCED VELOCITY, FPS | VIC | 13.660 |
| SPANWISE INDUCED VELOCITY, FPS | VIS | -29.456 |
| TOTAL NORMAL VELOCITY, FPS | VN | 62.50 |
| TOTAL CHORDWISE VELOCITY,FPS | VC | -685.98 |
| TOTAL SPANWISE VELOCITY,FPS | VS | 1041.35 |
| INPUT RADIAL VELOCITY,FPS | UR | 68.90 |
| INPUT TANGENTIAL VELOCITY,FPS | UT | 896.69 |
| INPUT AXIAL VELOCITY,FPS | UZ | 915.38 |
| RESULTANT VELOCITY, FPS | VTT | 1248.55 |
| SKEW ANGLE(BLADE ELEMENT),DEG | SKEW | 56.63 |
| CIRCULATION, FT SQ/SEC. | GAMMA | 8.83 |
| BLADE ELEMENT INFLOW ANGLE,DEG. | PHI | -4.307 |
| BL. ELEMENT ANG. OF ATTACK, DEG. | ALPHA | 5.206 |
| MACH NUMBER | CMACH | 1.1325 |
| BLADE ELEMENT MACH NUMBER | SMACH | .6248 |
| SECTION SPEED OF SOUND RATIO | SOUN | .99395 |
| SECTION DENSTY RATIO | DENS | .97021 |
| TIP MACH CONE CORRECTION | K-CONE | .495 |
| LIFT COEF. (BLADE ELEMENT) | CL | .3042 |
| DRAG COEF. (BLADE ELEMENT) | CD | .0364 |
| MIN. DRAG COEF. (BLADE ELEMENT) | CD | .0054 |

| | | |
|---|---|---|
| THRUST COEFFICIENT GRADIENT | DCT/DX | .1471 |
| POWER COEFFICIENT GRADIENT | DCP/DX | .6451 |

BLADE CHARACTERISTICS

| | | |
|---|---|---|
| THRUST PER BLADE, LBS | T/B | 30.0 |
| TORQUE PER BLADE, FT-LBS | Q/B | 42.8 |
| POWER PER BLADE, FT-LB/SEC | P/B | .3781+05 |
| HORSEPOWER PER BLADE, HP | HP/B | 68.7 |

INSTANTEOUS TOTAL PROPELLER PERFORMANCE FOR PROPELLER POSITION 1

| | | | | | |
|---|---|---|---|---|---|
| THRUST,LBS | 239.98 | POWER,FT-LB/SEC | .3025+06 | HORSEPOWER | 549.95 |

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            INTEGRATED PROPELLER CHARACTERISTICS FOR PROPELLER 1

THRUST, LBS            T      240.0    THRUST COEFFICIENT   CT      .3767    FORWARD VELOCITY    VKT   520.4
TORQUE, FT-LBS         Q      342.2    POWER COEFFICIENT    CP     1.6530    ADVANCE RATIO         J   3.059
PROFILE TORQUE         QO      18.9    EFFICIENCY         CT*J/CP   .6969    REFERENCE BLADE ANGLE    59.338
INDUCED TORQUE         QI     323.3
POWER, FT-LBS/SEC      P   .3025+06
HORSEPOWER, HP         HP     550.0
MOM. INDUCED VEL. FPS        -21.97

NACELLE PRESSURE DRAG,LBS   DPR      -43.11    NACELLE PRESSURE DRAG COEFF.    CDPR  -.06766
NACELLE FRICTION DRAG,LBS   DFR         .00    NACELLE FRICTION DRAG COEFF.    CDFR   .00000
COMBINED NACELLE DRAG,LBS DNAC       -43.11    COMBINED NACELLE DRAG COEFF.   CDNAC  -.06766
NACELLE AND PROPELLER THRUST,LBS TTOT     253.09      NACELLE AND PROPELLER THRUST COEFFICIENT   .44432
NACELLE AND PROPELLER POWER, FT-LBS/SEC  .3025+06      NACELLE AND PROPELLER POWER COEFFICIENT   1.65301
NACELLE AND PROPELLER HORSEPOWER ,HP      550.0
NACELLE AND PROPELLER EFFICIENCY          .8221

    FORCE PER BLADE PER UNIT SPAN

                 PROPELLER 1

                 RADIAL       TANGENTIAL      AXIAL

RS= .263        .5943+00      .2347+01      -.2900+01
RS= .327        .2737+00     -.1257+02       .1609+01
RS= .409        .1136+01     -.3481+02       .3774+01
RS= .490        .9226+00     -.5494+02       .1527+02
RS= .572        .1145+01     -.8942+02       .3762+02
RS= .653        .1066+01     -.1082+03       .5407+02
RS= .735        .3221+00     -.1349+03       .7528+02
RS= .816       -.1555+01     -.1458+03       .8960+02
RS= .899       -.3518+01     -.1048+03       .6692+02
RS= .962       -.9261+00     -.4089+02       .2922+02
RS= .994       -.3352+00     -.1612+02       .1148+02

TIME TO COMPUTE PERFORMANCE IS 1.21 SEC

TIME TO COMPLETE TOTAL PROGRAM: 49.34 SECONDS
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(9) Output of the Propeller Blade Forces

FORCE DEBUG

| FRCI(N,1) | FRCI(N,2) | FRCI(N,3) | FRC(N,1) | FRC(N,2) | FRC(N,3) |
|---|---|---|---|---|---|
| .59434+00 | .23472+01 | -.29003+01 | .14454-03 | .57082-03 | -.70533-03 |
| .43463+00 | -.51127+01 | -.64567+00 | .10555-03 | -.12434-02 | -.15702-03 |
| .70466+00 | -.23692+02 | .26914+01 | .17137-03 | -.57617-02 | .65454-03 |
| .10291+01 | -.44677+02 | .95196+01 | .25027-03 | -.10914-01 | .23151-02 |
| .10337+01 | -.72183+02 | .26444+02 | .25140-03 | -.17554-01 | .64311-02 |
| .11152+01 | -.98833+02 | .45645+02 | .27122-03 | -.24035-01 | .11149-01 |
| .70386+00 | -.12157+03 | .64675+02 | .17117-03 | -.29566-01 | .15728-01 |
| -.61658+00 | -.14037+03 | .82442+02 | -.14995-03 | -.34137-01 | .20049-01 |
| -.25367+01 | -.12534+03 | .78260+02 | -.61690-03 | -.30482-01 | .19032-01 |
| -.22221+01 | -.72667+02 | .48069+02 | -.54040-03 | -.17721-01 | .11690-01 |
| -.63065+00 | -.28507+02 | .20349+02 | -.15337-03 | -.69326-02 | .49486-02 |
| .00000 | .00000 | .00000 | .00000 | .00000 | .00000 |

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(10) Output of the Nacell Viscous Flow Solution (At Axial Station ZH = .76489)



GAP AVERAGED FLOW PROPERTIES

ZH= .76489+00 CFSH= .44437-02 CFPH= .00000 STSH= .00000 AMH= .00000
ZT= .70159+01 CFST=-.14708-04 CFPT= .00000 STST= .00000 AMT= .00000

| Y | US | UPI, | ALPHA | PI | THETA | MACH | PIO | THETAO | PRES. COEF. |
|---|---|---|---|---|---|---|---|---|---|
| .00000 | .33976-19 | .00000 | .00000 | .79731+00 | .11016+01 | .00000 | .79731+00 | .11016+01 | .71369-01 |
| .21652-05 | .10938+00 | .00000 | .00000 | .79731+00 | .11010+01 | .61932-01 | .79945+00 | .11019+01 | .71369-[illegible] |
| .60546-05 | .26425+00 | .00000 | .00000 | .79731+00 | .10965+01 | .15020+00 | .80997+00 | .11035+01 | .7136[illegible] |
| .13041-04 | .50932+00 | .00000 | .00000 | .79731+00 | .10902+01 | .29088+00 | .84555+00 | .11087+01 | .71368-01 |
| .25590-04 | .71057+00 | .00000 | .00000 | .79731+00 | .10780+01 | .40771+00 | .89402+00 | .11138+01 | .71368-01 |
| .48132-04 | .75304+00 | .00000 | .00000 | .79731+00 | .10747+01 | .43274+00 | .90682+00 | .11149+01 | .71360-01 |
| .88621-04 | .83206+00 | .00000 | .00000 | .79731+00 | .10672+01 | .47983+00 | .93339+00 | .11163+01 | .71361-01 |
| .16134-03 | .88886+00 | .00000 | .00000 | .79730+00 | .10610+01 | .51407+00 | .95482+00 | .11171+01 | .71352-01 |
| .29195-03 | .98860+00 | .00000 | .00000 | .79730+00 | .10492+01 | .57497+00 | .99759+00 | .11186+01 | .71332-01 |
| .52648-03 | .11459+01 | .00000 | .00000 | .79728+00 | .10276+01 | .67338+00 | .10804+01 | .11209+01 | .71286-01 |
| .94751-03 | .12886+01 | .00000 | .00000 | .79723+00 | .10044+01 | .76595+00 | .11756+01 | .11223+01 | .71175-01 |
| .17030-02 | .13049+01 | .00000 | .00000 | .79714+00 | .99948+00 | .77756+00 | .11887+01 | .11204+01 | .70946-01 |
| .30574-02 | .12954+01 | .00000 | .00000 | .79698+00 | .10018+01 | .77098+00 | .11809+01 | .11210+01 | .70534-01 |
| .54816-02 | .13139+01 | .00000 | .00000 | .79669+00 | .99963+00 | .78289+00 | .11942+01 | .11222+01 | .69791-01 |
| .98089-02 | .12921+01 | .00000 | .00000 | .79617+00 | .10009+01 | .76937+00 | .11779+01 | .11195+01 | .68468-01 |
| .17495-01 | .13163+01 | .00000 | .00000 | .79524+00 | .99877+00 | .78465+00 | .11941+01 | .11218+01 | .66119-01 |
| .31025-01 | .13054+01 | .00000 | .00000 | .79361+00 | .99832+00 | .77632+00 | .11843+01 | .11193+01 | .61973-01 |
| .53903-01 | .13020+01 | .00000 | .00000 | .79083+00 | .99703+00 | .77678+00 | .11784+01 | .11174+01 | .54929-01 |
| .91119-01 | .13098+01 | .00000 | .00000 | .78600+00 | .99408+00 | .78262+00 | .11779+01 | .11159+01 | .42660-01 |
| .15069+00 | .13024+01 | .00000 | .00000 | .77919+00 | .99201+00 | .77899+00 | .11635+01 | .11125+01 | .25390-01 |
| .23955+00 | .13231+01 | .00000 | .00000 | .77306+00 | .98893+00 | .79260+00 | .11699+01 | .11132+01 | .98348-02 |
| .35945+00 | .13140+01 | .00000 | .00000 | .76970+00 | .98824+00 | .78742+00 | .11589+01 | .11108+01 | .13079-02 |
| .50077+00 | .13301+01 | .00000 | .00000 | .76833+00 | .98721+00 | .79751+00 | .11684+01 | .11128+01 | -.21741-02 |
| .64256+00 | .13173+01 | .00000 | .00000 | .76773+00 | .98747+00 | .78975+00 | .11565+01 | .11107+01 | -.36763-02 |
| .76338+00 | .13315+01 | .00000 | .00000 | .76744+00 | .98692+00 | .79848+00 | .11681+01 | .11128+01 | -.44244-02 |
| .85279+00 | .13181+01 | .00000 | .00000 | .76730+00 | .98730+00 | .79029+00 | .11585+01 | .11107+01 | -.47760-02 |
| .91232+00 | .13316+01 | .00000 | .00000 | .76724+00 | .98688+00 | .79853+00 | .11679+01 | .11128+01 | -.49215-02 |
| .94922+00 | .13184+01 | .00000 | .00000 | .76722+00 | .98727+00 | .79046+00 | .11586+01 | .11107+01 | -.49757-02 |
| .97108+00 | .13312+01 | .00000 | .00000 | .76721+00 | .98686+00 | .79830+00 | .11676+01 | .11127+01 | -.49964-02 |
| .98369+00 | .13189+01 | .00000 | .00000 | .76721+00 | .98731+00 | .79077+00 | .11589+01 | .11108+01 | -.50069-02 |
| .99086+00 | .13302+01 | .00000 | .00000 | .76721+00 | .98684+00 | .79772+00 | .11669+01 | .11125+01 | -.50129-02 |
| .99489+00 | .13206+01 | .00000 | .00000 | .76721+00 | .98747+00 | .79167+00 | .11599+01 | .11113+01 | -.50163-02 |
| .99715+00 | .13276+01 | .00000 | .00000 | .76720+00 | .98649+00 | .79629+00 | .11652+01 | .11116+01 | -.50182-02 |
| .99841+00 | .13244+01 | .00000 | .00000 | .76720+00 | .98639+00 | .79444+00 | .11631+01 | .11110+01 | -.50192-02 |
| .99912+00 | .13213+01 | .00000 | .00000 | .76720+00 | .98760+00 | .79205+00 | .11604+01 | .11116+01 | -.50198-02 |
| .99951+00 | .13223+01 | .00000 | .00000 | .76720+00 | .98853+00 | .79231+00 | .11607+01 | .11127+01 | -.50201-02 |
| .99973+00 | .13210+01 | .00000 | .00000 | .76720+00 | .98930+00 | .79121+00 | .11594+01 | .11132+01 | -.50203-02 |
| .99985+00 | .13210+01 | .00000 | .00000 | .76720+00 | .98963+00 | .79108+00 | .11593+01 | .11136+01 | -.50204-02 |
| .99992+00 | .13211+01 | .00000 | .00000 | .76720+00 | .98992+00 | .79101+00 | .11592+01 | .11139+01 | -.50205-02 |
| .99996+00 | .13212+01 | .00000 | .00000 | .76720+00 | .98988+00 | .79108+00 | .11593+01 | .11138+01 | -.50205-02 |
| .99998+00 | .13212+01 | .00000 | .00000 | .76720+00 | .98984+00 | .79113+00 | .11593+01 | .11138+01 | -.50205-02 |
| .99999+00 | .13213+01 | .00000 | .00000 | .76720+00 | .98987+00 | .79114+00 | .11593+01 | .11138+01 | -.50205-02 |
| .99999+00 | .13213+01 | .00000 | .00000 | .76720+00 | .98993+00 | .79113+00 | .11593+01 | .11139+01 | -.50205-02 |
| .10000+01 | .13213+01 | .00000 | .00000 | .76720+00 | .98992+00 | .79114+00 | .11593+01 | .11139+01 | -.50205-02 |
| .10000+01 | .13213+01 | .00000 | .00000 | .76720+00 | .98983+00 | .79118+00 | .11594+01 | .11138+01 | -.50205-02 |

SOLVI CALCULATION BETWEEN PRINTOUT
TIME -225 232.59220
NUMBER OF STATIONS = 41

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OF POOR QUALITY

GAP AVERAGED FLOW PROPERTIES

| Y | PSI | IOTA | MU | LAMB | YPLUS | UPLUS | TPLUS | QPLUS |
|---|---|---|---|---|---|---|---|---|
| .00000 | .00000 | .56493+00 | .10770+01 | .14956+01 | .00000 | .00000 | .10000+01 | .00000 |
| .21652-05 | .26959-07 | .56325+00 | .10899+01 | .15128+01 | .15096+01 | .16870+01 | .10138+01 | .24782+00 |
| .60546-05 | .17029-06 | .55536+00 | .11556+01 | .15855+01 | .42212+01 | .40868+01 | .10387+01 | .59371+00 |
| .13041-04 | .70607-06 | .52877+00 | .18922+01 | .24027+01 | .90921+01 | .78846+01 | .10545+01 | .95477+00 |
| .25590-04 | .22372-05 | .48920+00 | .80337+01 | .92241+01 | .17841+02 | .10989+02 | .13582+01 | .15423+01 |
| .48132-04 | .55707-05 | .47850+00 | .12796+02 | .14512+02 | .33557+02 | .11646+02 | .60163+00 | .93845+00 |
| .88621-04 | .12109-04 | .45396+00 | .28923+02 | .32429+02 | .61786+02 | .12868+02 | .84652+00 | .14749+01 |
| .16134-03 | .24956-04 | .43378+00 | .45753+02 | .51127+02 | .11249+03 | .13747+02 | .65934+00 | .17057+01 |
| .29195-03 | .50396-04 | .39451+00 | .45743+02 | .51113+02 | .20355+03 | .15289+02 | .78539+00 | .17630+01 |
| .52648-03 | .10334-03 | .32194+00 | .45727+02 | .51091+02 | .36706+03 | .17721+02 | .51045+00 | .13165+01 |
| .94751-03 | .21495-03 | .24195+00 | .45713+02 | .51072+02 | .66060+03 | .19928+02 | .15091+00 | .46098+00 |
| .17030-02 | .43408-03 | .22489+00 | .45707+02 | .51064+02 | .11873+04 | .20181+02 | .38532-02 | .23431-01 |
| .30574-02 | .63715-03 | .23331+00 | .45707+02 | .51064+02 | .21316+04 | .20033+02 | .29273-02 | -.79132-03 |
| .54816-02 | .15690-02 | .22600+00 | .45707+02 | .51064+02 | .38216+04 | .20321+02 | .27900-03 | .25628-02 |
| .98089-02 | .30184-02 | .23118+00 | .45707+02 | .51063+02 | .68387+04 | .19983+02 | .47702-03 | .13803-02 |
| .17495-01 | .58397-02 | .22479+00 | .45706+02 | .51062+02 | .12197+05 | .20357+02 | .95491-03 | .23477-02 |
| .31025-01 | .11668-01 | .22527+00 | .45705+02 | .51061+02 | .21630+05 | .20189+02 | .17378-03 | .90030-03 |
| .53903-01 | .23960-01 | .22426+00 | .45704+02 | .51059+02 | .37581+05 | .20136+02 | .34158-03 | .13052-02 |
| .91119-01 | .50340-01 | .22002+00 | .45702+02 | .51057+02 | .63528+05 | .20257+02 | .25369-03 | .94855-03 |
| .15069+00 | .11035+00 | .22144+00 | .45700+02 | .51054+02 | .10506+06 | .20142+02 | .27010-03 | .62534-03 |
| .23955+00 | .23695+00 | .21844+00 | .45698+02 | .51051+02 | .16702+06 | .20462+02 | .14745-03 | .31712-03 |
| .35945+00 | .47746+00 | .22038+00 | .45697+02 | .51050+02 | .25061+06 | .20321+02 | .61763-04 | .11274-03 |
| .50077+00 | .86129+00 | .21850+00 | .45696+02 | .51049+02 | .22494+05 | .37002+03 | .75802-02 | .25099+00 |
| .64256+00 | .13563+01 | .22020+00 | .45696+02 | .51048+02 | .16105+05 | .36647+03 | .35994-02 | .10096+00 |
| .76338+00 | .18690+01 | .21865+00 | .45696+02 | .51048+02 | .10662+05 | .37042+03 | .23892-02 | .79926-01 |
| .85279+00 | .23663+01 | .22015+00 | .45696+02 | .51048+02 | .66328+04 | .36668+03 | .91133-03 | .31974-01 |
| .91232+00 | .26264+01 | .21873+00 | .45696+02 | .51048+02 | .39506+04 | .37043+03 | .14006-02 | .32782-01 |
| .94922+00 | .28371+01 | .22014+00 | .45696+02 | .51048+02 | .22882+04 | .36676+03 | .16249-02 | .20987-01 |
| .97108+00 | .29665+01 | .21873+00 | .45696+02 | .51048+02 | .13032+04 | .37032+03 | .55943-02 | -.12351+00 |
| .98369+00 | .30427+01 | .22030+00 | .45696+02 | .51048+02 | .73484+03 | .36691+03 | .16358-01 | .12169+00 |
| .99086+00 | .30865+01 | .21865+00 | .45696+02 | .51048+02 | .41201+03 | .37005+03 | .48456-01 | -.15272+01 |
| .99489+00 | .31114+01 | .22089+00 | .45696+02 | .51048+02 | .23025+03 | .36736+03 | .13985+00 | .58549+01 |
| .99715+00 | .31253+01 | .21740+00 | .45696+02 | .51048+02 | .12842+03 | .36932+03 | .37111+00 | .32174+02 |
| .99841+00 | .31332+01 | .21704+00 | .45696+02 | .51048+02 | .71532+02 | .36844+03 | .10845+01 | -.58977+02 |
| .99917+00 | .31375+01 | .22134+00 | .45696+02 | .51049+02 | .39799+02 | .36756+03 | .65110+00 | -.20401+03 |
| .99951+00 | .31400+01 | .22462+00 | .45697+02 | .51050+02 | .22114+02 | .36785+03 | .13968+00 | -.29083+03 |
| .99973+00 | .31413+01 | .22735+00 | .45698+02 | .51050+02 | .12263+02 | .36749+03 | .13014+01 | -.34064+03 |
| .99985+00 | .31421+01 | .22654+00 | .45698+02 | .51051+02 | .67774+01 | .36748+03 | .14956+00 | -.34511+03 |
| .99992+00 | .31425+01 | .22956+00 | .45698+02 | .51051+02 | .37229+01 | .36751+03 | .55327+00 | -.24755+03 |
| .99996+00 | .31427+01 | .22942+00 | .45698+02 | .51051+02 | .20220+01 | .36753+03 | .81032+00 | .14809+03 |
| .99998+00 | .31428+01 | .22926+00 | .45698+02 | .51051+02 | .10755+01 | .36755+03 | .92499+00 | .55915+02 |
| .99999+00 | .31429+01 | .22936+00 | .45698+02 | .51051+02 | .54808+00 | .36756+03 | .99136+00 | -.53371+03 |
| .99999+00 | .31430+01 | .22959+00 | .45698+02 | .51051+02 | .25463+00 | .36756+03 | .10284+01 | -.52842+03 |
| .10000+01 | .31430+01 | .22954+00 | .45698+02 | .51051+02 | .90938-01 | .36757+03 | .10102+01 | .16397+04 |
| .10000+01 | .31430+01 | .22923+00 | .99209+00 | .13779+01 | .00000 | .36757+03 | .10000+01 | .00000 |

TRUNCATION ERROR

EROTH= .26016-03 EPRES= .28047-03 FROUS= .21207-02 EUSUS= .23017-01 EUFUP= .00000 EENTP= .53179-03

YPLUSH= .15096+01 YPLUST= .90938-01

APPENDIX C

List of Symbols

| | |
|---|---|
| $a$ | transformation variable |
| $A$ | Area, $a/r_r^2$ (dimensionless) |
| $A+$ | Van Driest constant (26.0) |
| $a_I$, $b_I$ | Schwartz-Christoffel parameters |
| $\overset{=}{A}$ | Block tridiagonal matrix (dimensionless) |
| $\overset{=}{A}{}^k$ | Diagonal block matrix (dimensionless) |
| $B$ | chord, $b/r_r$ (dimensionless) |
| $\overset{=}{B}{}^k$ | Left diagonal block matrix (dimensionless) |
| $C$ | Speed of sound (ft/sec) |
| $C_{fr}$ | Wall friction drag coefficient |
| $c_p$ | Specific heat pressure ($ft^2/sec^2$/deg R) |
| $C_p$ | Pressure drag coefficient |
| $c_V$ | Specific heat volume ($ft^2/sec^2$/deg R) |
| $D_{Fr}$ | Friction drag |
| $D_{Pr}$ | Pressure drag |
| $e_{ns}$ | Streamwise strain (1/sec) |
| $E_{ns}$ | Streamwise strain, $r_r e_{ns}/u_r$ (dimensionless) |
| $e_{n\phi}$ | Tangential strain (1/sec) |
| $E_{n\phi}$ | Tangential strain, $r_r e_{n\phi}/u_r$ (dimensionless) |
| $f$ | force/span |
| $F$ | Complex potential ($s + i n$), body force |

| | |
|---|---|
| $g_B$ | Gap between blades (ft) |
| G | Gap between blades, $g_B/r_r$ (dimensionless) |
| h | Duct height |
| I | Entropy |
| m | Mass flow (slugs/sec) |
| M | Mass flow, $m/(N_B r_r^2 \rho_r U_r)$ (dimensionless) |
| M | Mach number, U/C (dimensionless) |
| $\overset{o}{m}$ | Mass flow/area (slugs/ft$^2$/sec) |
| $m^+$ | Universal mass flow parameter, $\overset{o}{m}_w/(\rho_w U^*)$ (dimensionless) |
| $\overset{o}{M}$ | Mass flow/area, $\overset{o}{m}/(\rho_r U_r)$ (dimensionless) |
| n | Normal coordinate (dimensionless) |
| $N_B$ | Number of blades (dimensionless) |
| $N_R$ | Reynolds number, $r_r \rho_r U_r/\mu_r$ (dimensionless) |
| P | Pressure (lb/ft$^2$) |
| $P_o$ | Total pressure |
| $Pr_T$ | Turbulent Prandtl number |
| Q | Heat flux, $q/(\rho_r U_r C_p T_r)$ (dimensionless) |
| $q_n$ | Heat flux |
| r | Radial coordinate |
| R | Radius, $r/r_r$ (dimensionless) |
| $\mathcal{R}$ | Gas constant (ft$^2$/sec$^2$/deg R) |
| s | Streamwise coordinate ( dimensionless) |

| | |
|---|---|
| $S$ | Streamwise coordinate, $s/(r_r V_r)$ (dimensionless) |
| St | Stanton number (dimensionless) |
| $T$ | Temperature (deg R) |
| $T_o$ | Total temperature |
| $U$ | Magnitude of velocity or velocity component |
| $U_\phi$ | Tangential velocity |
| $U^+$ | Universal velocity, $U/U^*$ (dimensionless) |
| $U^*$ | Friction velocity, $\sqrt{\tau\rho}/U_r$ (dimensionless) |
| $V$ | Potential flow velocity (1/V metric scale coefficient) |
| $W$ | Complex coordinates in duct plan $(r + iz)$ |
| $x$, $y$ | Distance along S and n coordinates |
| $Y^+$ | Universal distance |
| $z$ | Axial coordinate |
| $Z$ | Axial distance, $z/r_r$ (dimensionless) |
| $\alpha$ | Swirl angle to axis (deg) |
| $\gamma$ | Ratio of specific heats, $C_p/C_V$ (dimensionless) |
| $\Delta$ | Boundary layer thickness, $\delta/r_r$ (dimensionless) |
| $\Delta^*$ | Displacement thickness, $\delta^*/r_r$ (dimensionless) |
| $\eta$ | Normal coordinate, $n/(r_r V_r)$ (dimensionless), or Transformed normal coordinate (dimensionless) |

| | |
|---|---|
| $\theta$ | Angle of streamline to axis (deg) |
| $\Theta$ | Temperature ratio, $T/T_r$ (dimensionless) |
| $\Theta^*$ | Momentum thickness, $\Theta^*/T_r$ (dimensionless) |
| $i$ | $\sqrt{-1}$ |
| $I$ | Entropy, $(I-I_n)/R$ (dimensionless) |
| $\kappa$ | von Karman constant (0.41) |
| $\lambda$ | Thermal conductivity (lb/sec/deg R) |
| $\mu$ | Viscosity (slugs/ft/sec) |
| $\pi$ | 3.14159 |
| $\Pi$ | Pressure ratio, $p/p_r$ (dimensionless) |
| $\rho$ | Density (slugs/ft$^3$) |
| $P$ | Density ratio, $\rho/\rho_r$ (dimensionless) |
| $\Sigma_{ns}$ | Streamwise stress, $T_{ns}/(\rho_r U_r^2)$ (dimensionless) |
| $\Sigma_{n\phi}$ | Tangential stress, $T_{n\phi}/(\rho_r U_r^2)$ (dimensionless) |
| $\tau_{ns}, \tau_{n\phi}$ | Stress components |
| $\tau^+$ | Stress, $\tau/\tau_w$ (dimensionless) |
| $\phi$ | Tangential coordinate (radians) |
| $\phi_B$ | Blade dissipation function |
| $\chi$ | Clauser constant (0.016) (dimensionless), or Transformation function, $d\eta/dn$ (dimensionless) |
| $\Psi$ | Stream function (dimensionless) |

Matrix Operators

| | |
|---|---|
| T | Transpose |
| -1 | Inverse |

Superscripts

| | |
|---|---|
| $\nu$ | Iteration number |
| $-$ | Mean or average quantity |
| $\wedge$ | Variables for blade force calculation |
| ' | Deviation from mean quantity |

Subscripts

| | |
|---|---|
| 0 | Stagnation conditions |
| 1 | Inlet conditions |
| 2 | Upstream of strut blade |
| 3 | Downstream of strut blade |
| A | Adiabatic |
| E | Effective turbulent |
| H | Hub conditions |
| I | Incompressible conditions, singularity index |
| n | in the direction of the normal |
| r | Reference conditions, based on standard sea level atmosphere conditions for all thermodynamic quantities. The reference radius $r_r$ is the inlet outer radius, and the velocity is the mean inlet velocity |

Subscripts (Cont'd)

| | |
|---|---|
| s | in the streamwise direction |
| T | Tip conditions |
| W | Wall conditions |
| $\infty$ | Free Stream or edge of boundary layer |

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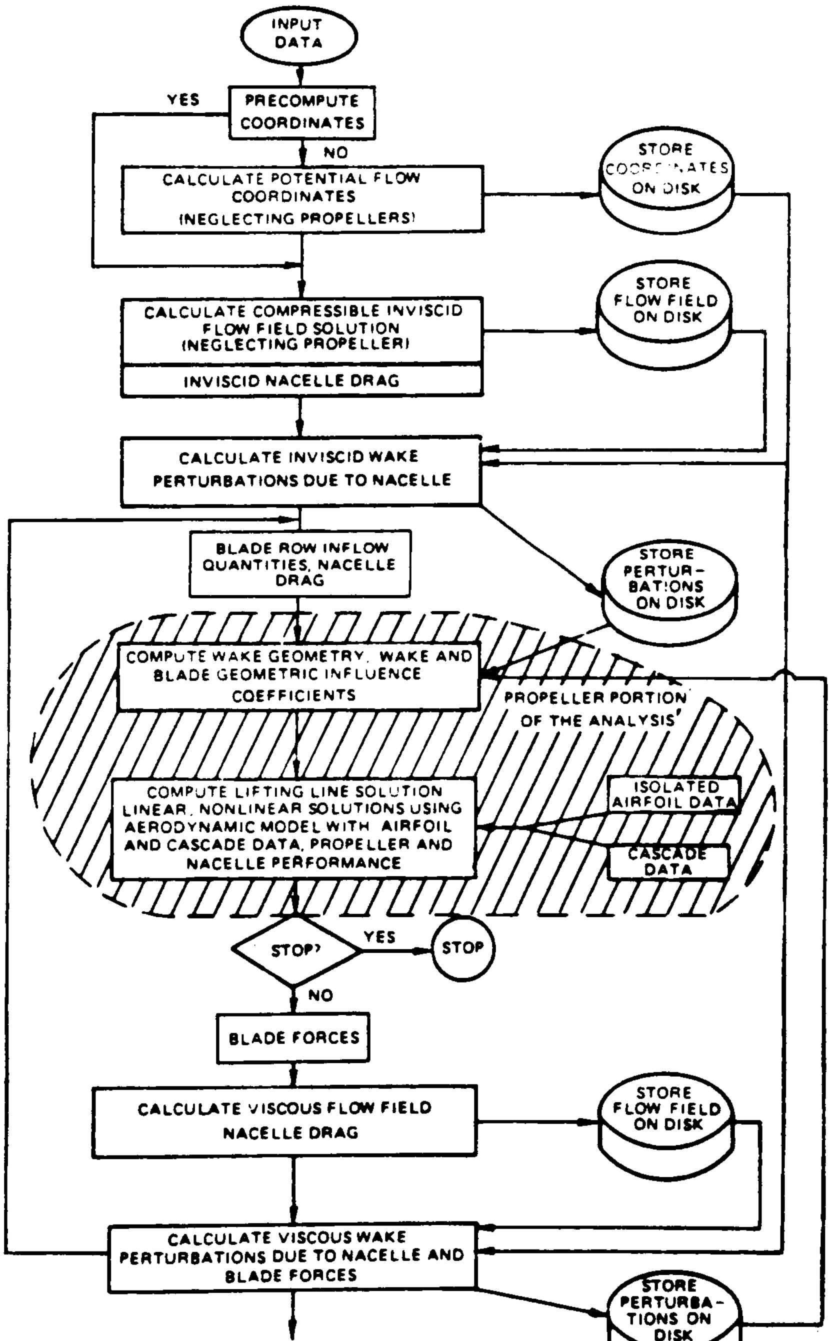



**Figure 1. Flow Diagram of the Combined Propeller-Nacelle Analysis**

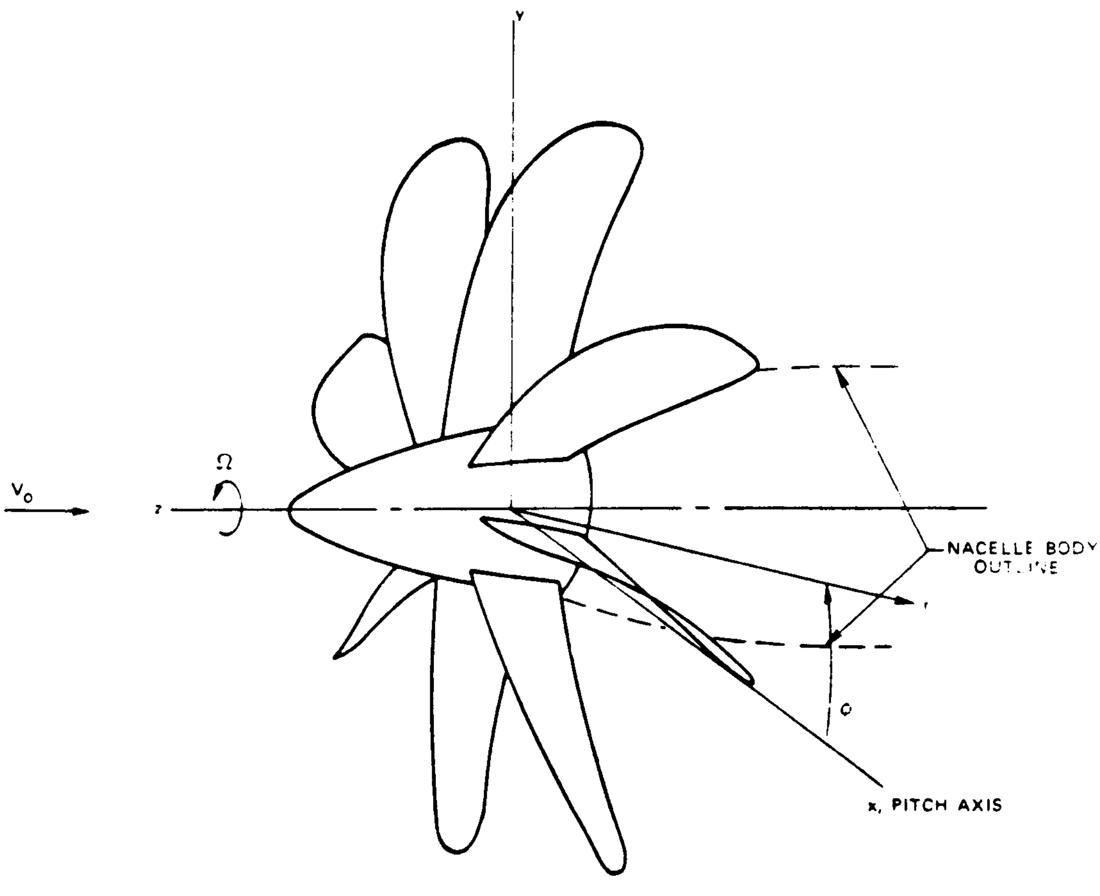



**Figure 2. Cylindrical and Cartesian Coordinate Systems for Propeller Geometry**

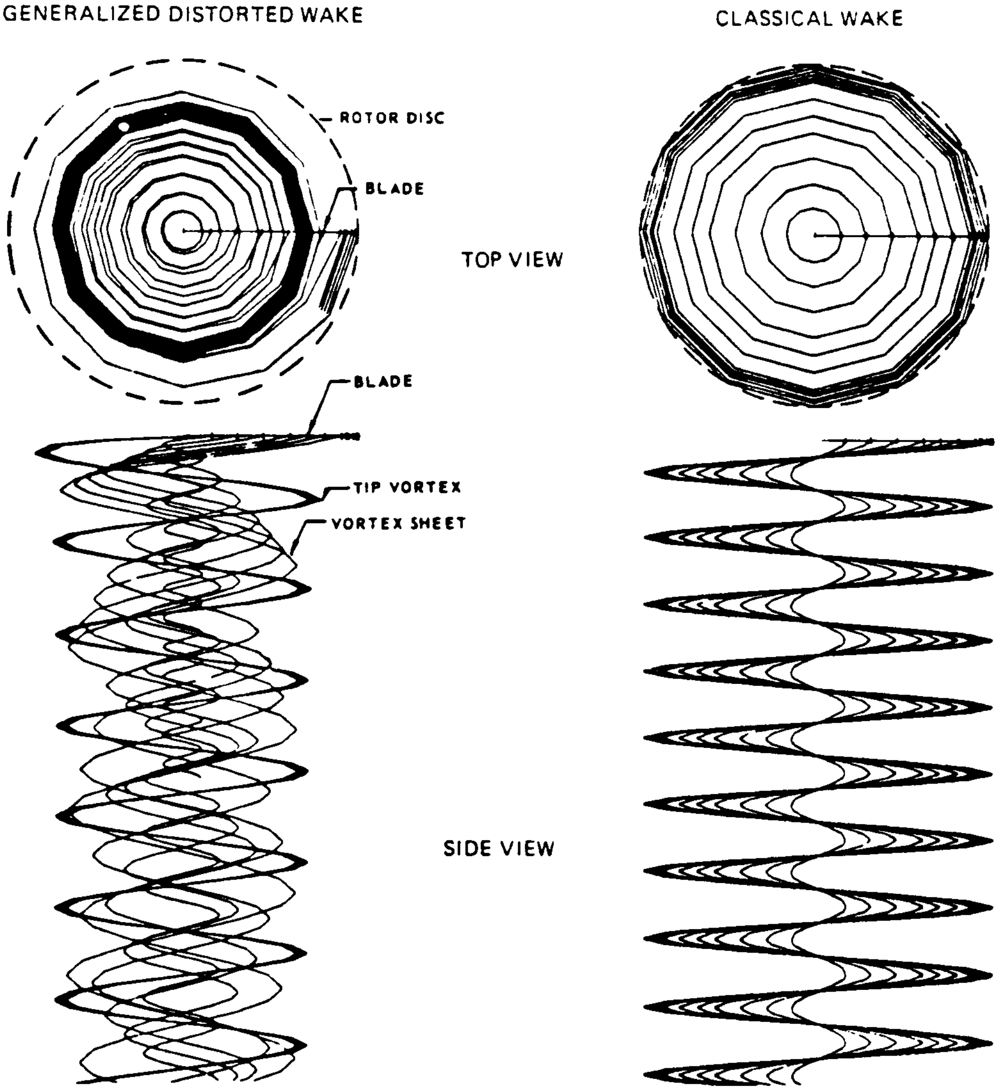



**Figure 3. Computer Wake Representation for One Blade of a Hovering Rotor, Classical and Generalized Distorted Wake Models**

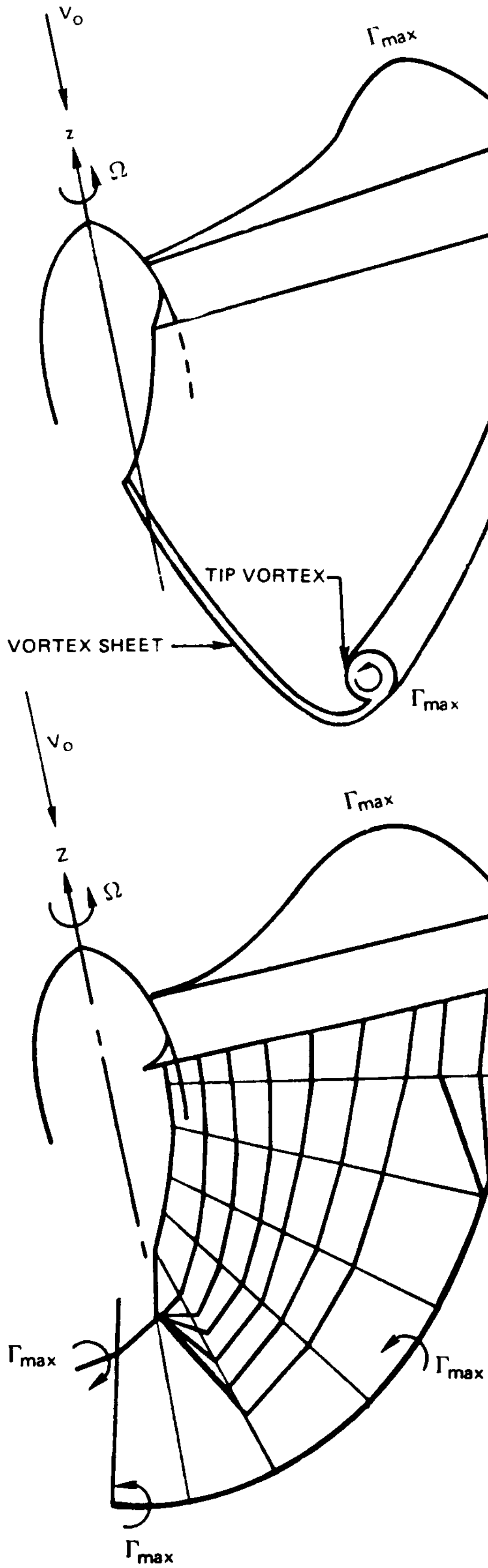



**Figure 4. Modeling the Wake Rollup with Discrete Vortices**

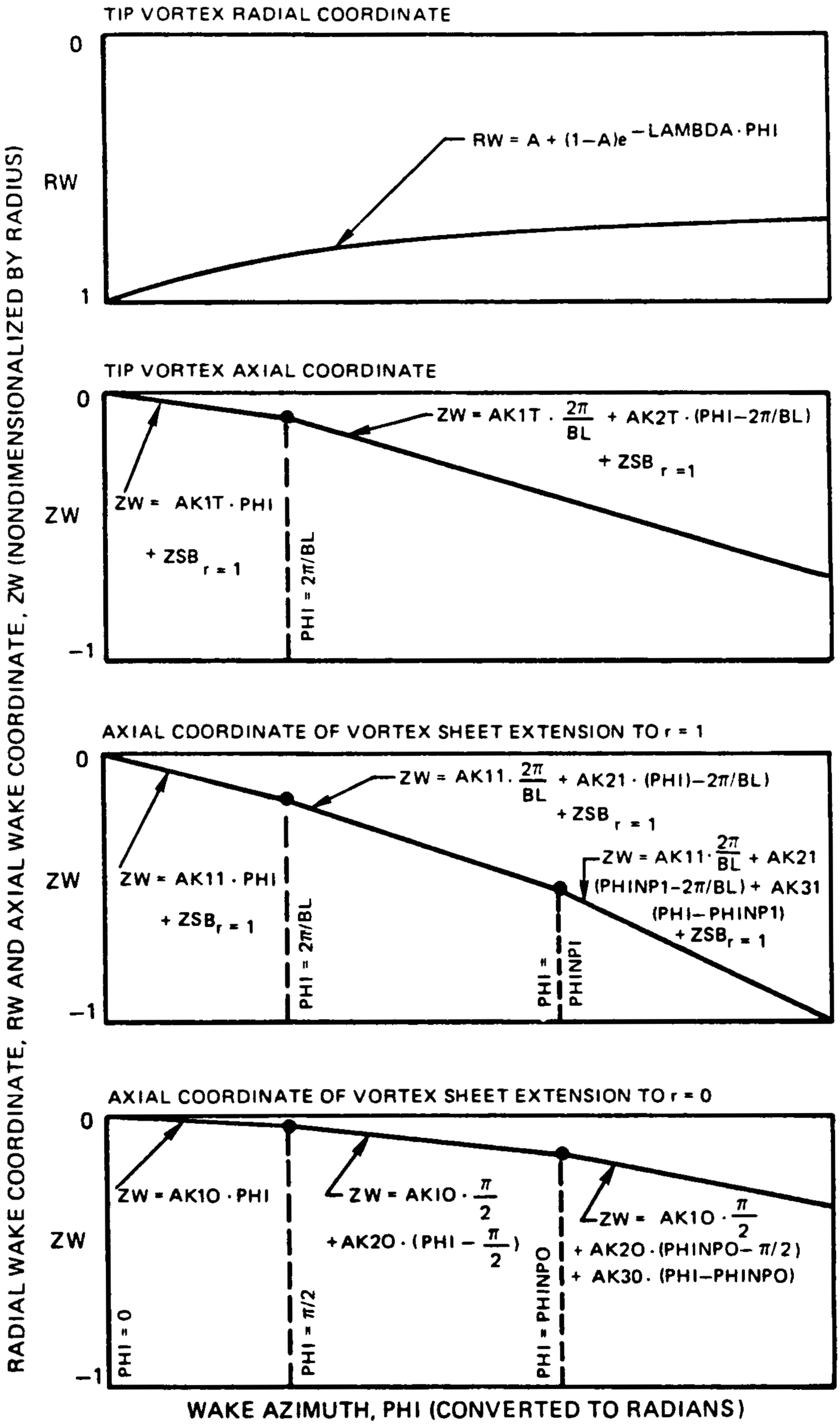
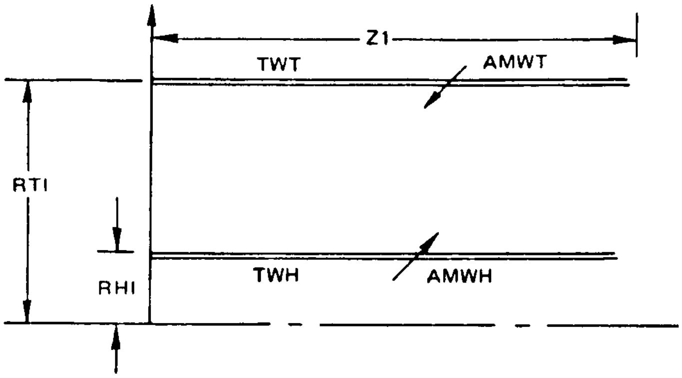


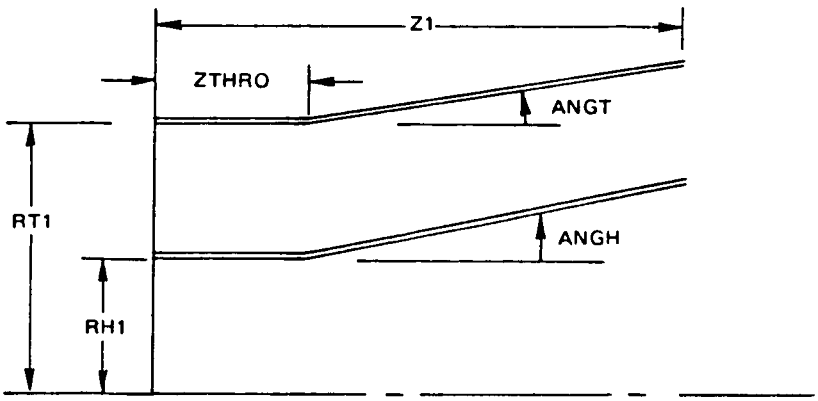

**Figure 5. Generalized Wake Geometry Equations Containing Input Wake Constants**



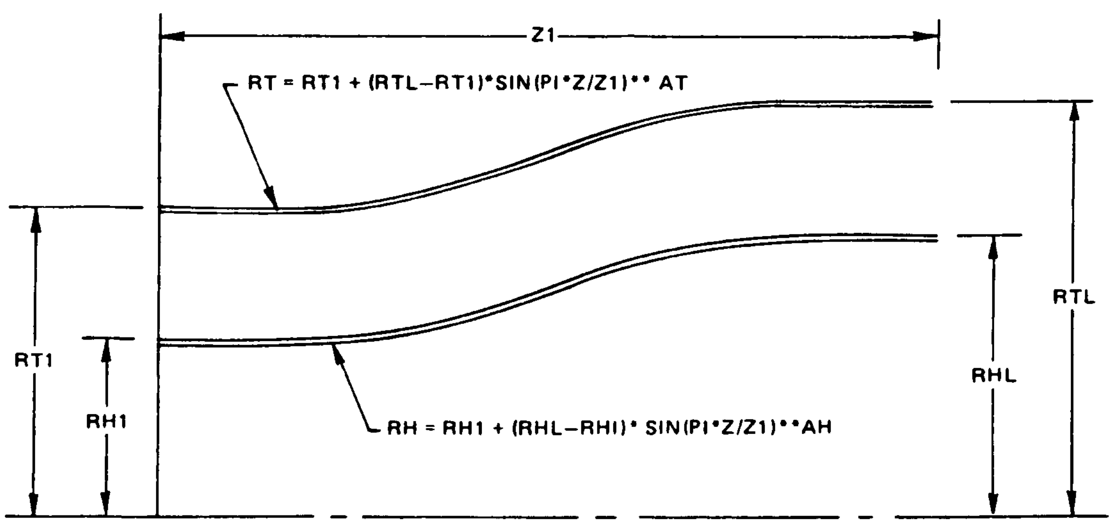
85—4—90—24




IOPT3 = 1    STRAIGHT ANNULAR DUCT




IOPT3 = 3    STRAIGHT WALL ANNULAR DIFFUSER




IOPT3 = 5    CURVED WALL DIFFUSER NO. 1

**Figure 6. Preprogrammed Duct Wall Contours**



85–4–90–25

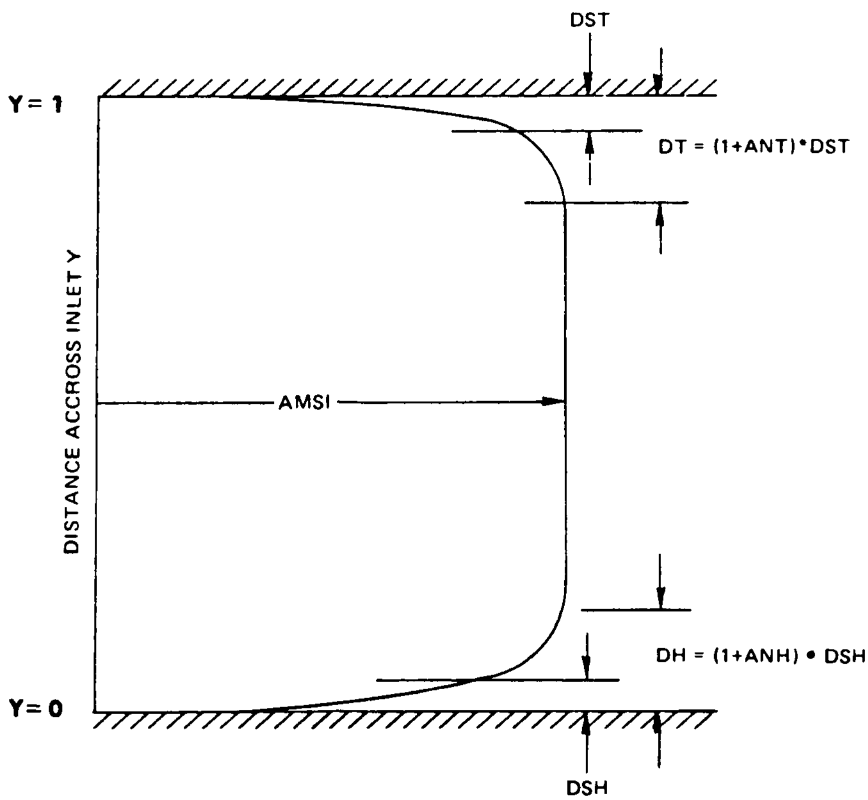



**Figure 7. Inlet FLow Distribution**

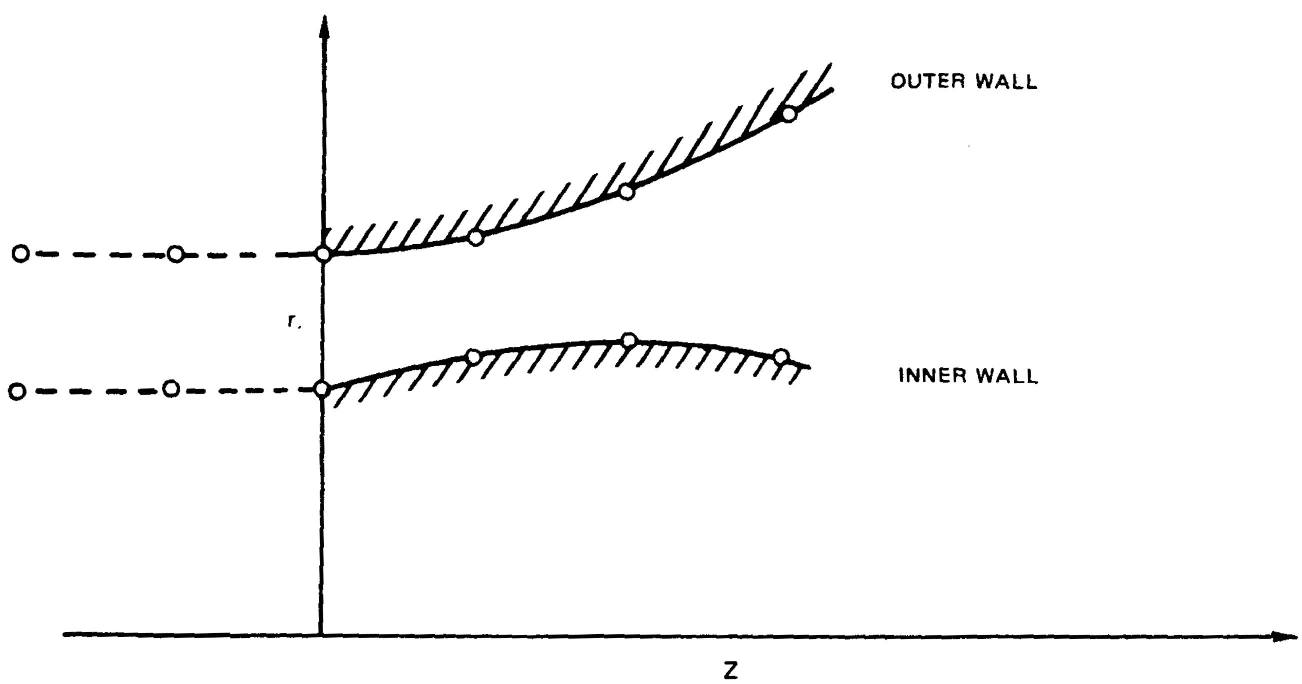



Figure 8. Addition of Straight Annular Channel Inlet

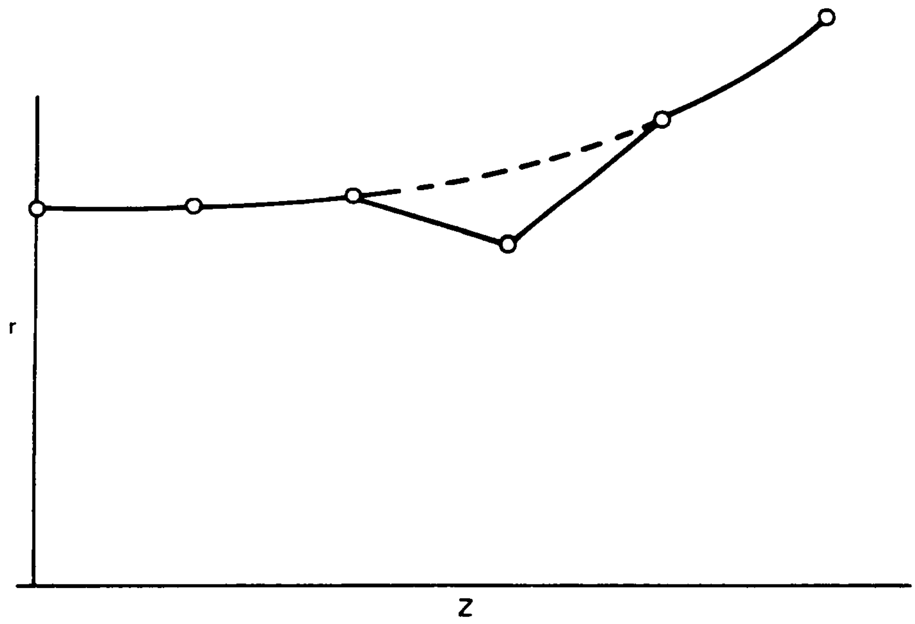



**Figure 9. Discontinuous Change in Wall Curvature**



85–4–90–28

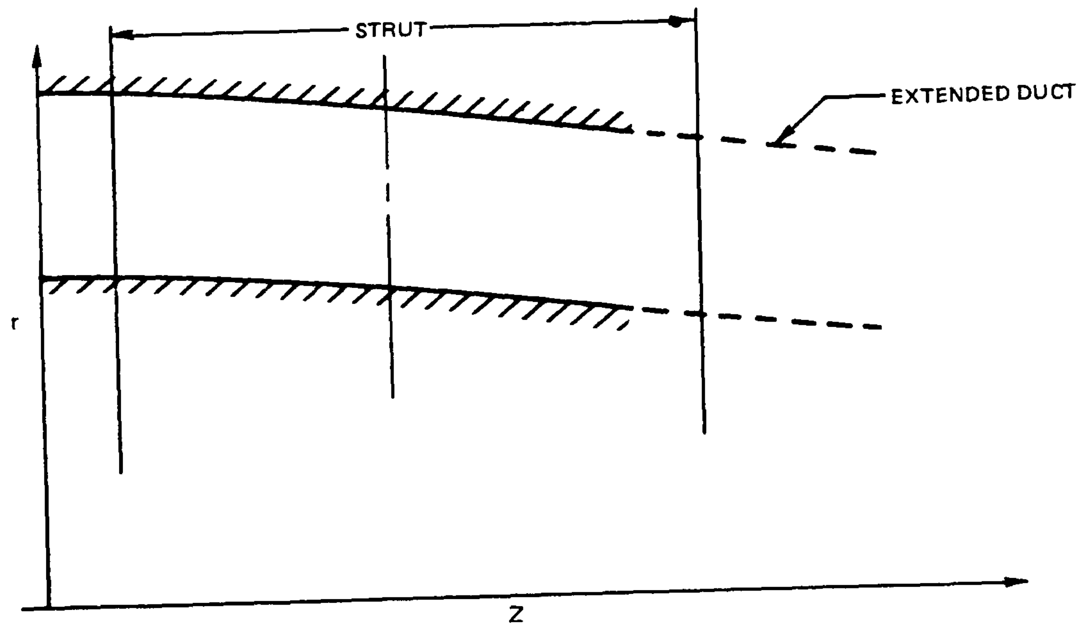



**Figure 10. Extended Duct Section**



85-4-90-29

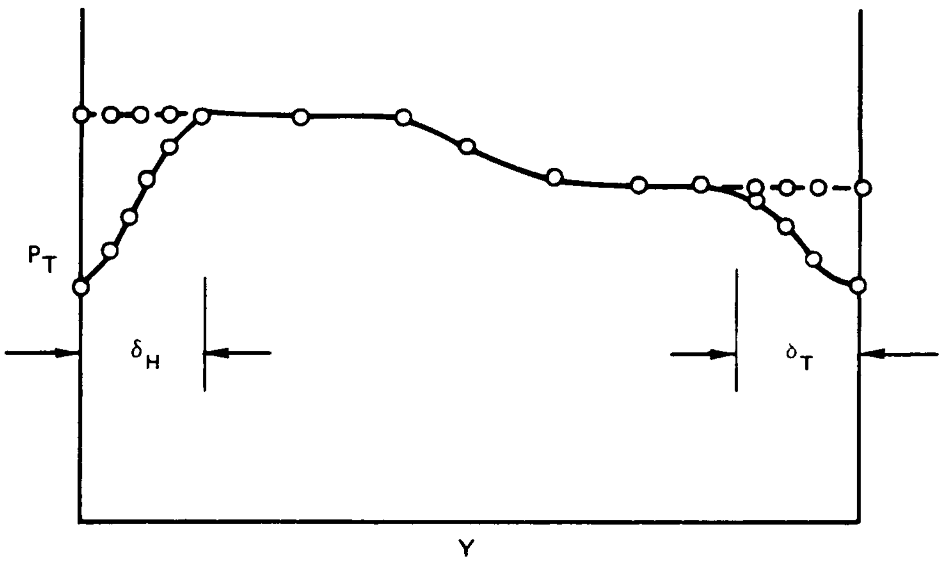



**Figure 11. Constructing the Inlet Flow**



C-4

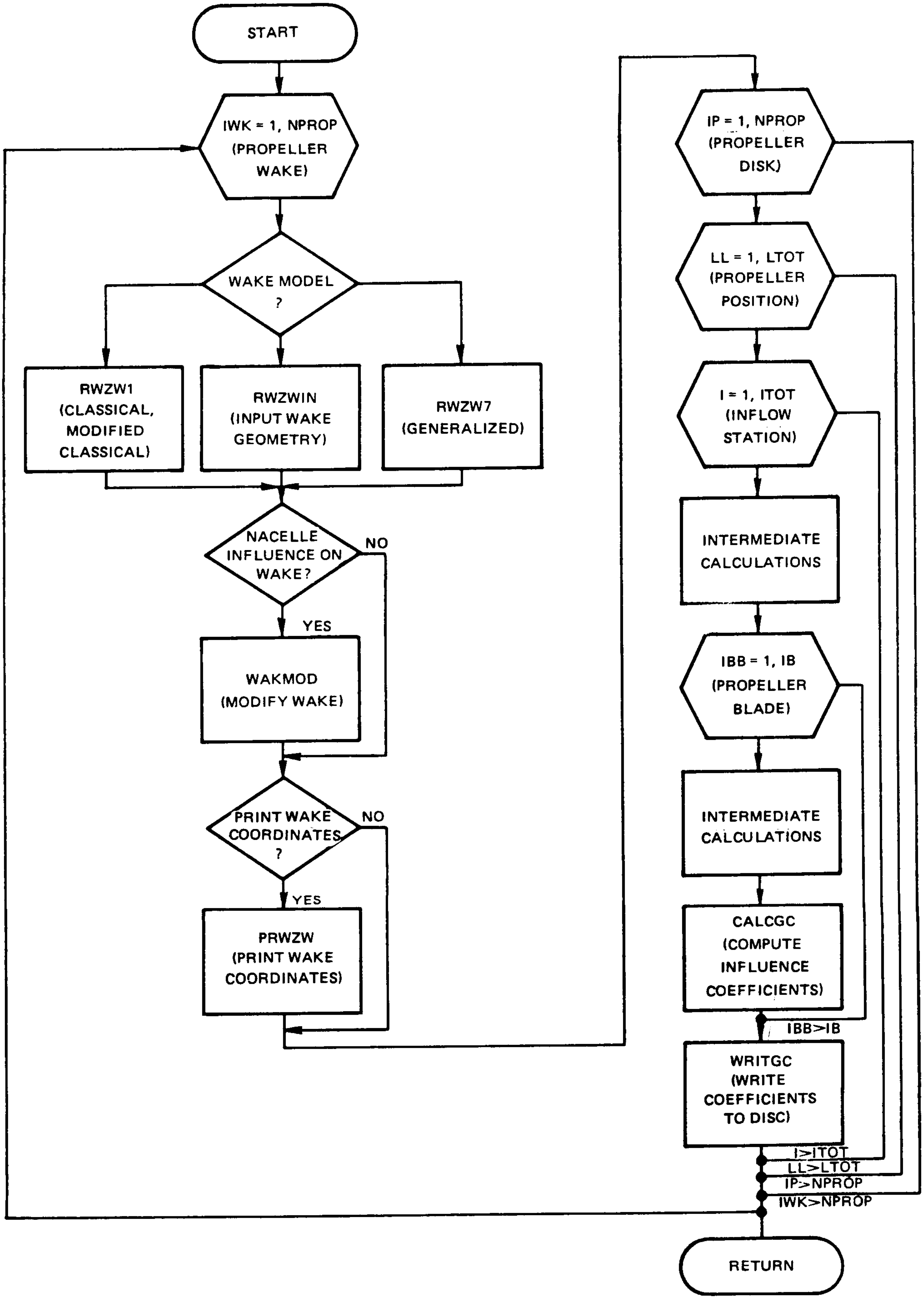



**Figure 12. Flow Diagram of Subroutine GCWAKE**

85–4–9C–31

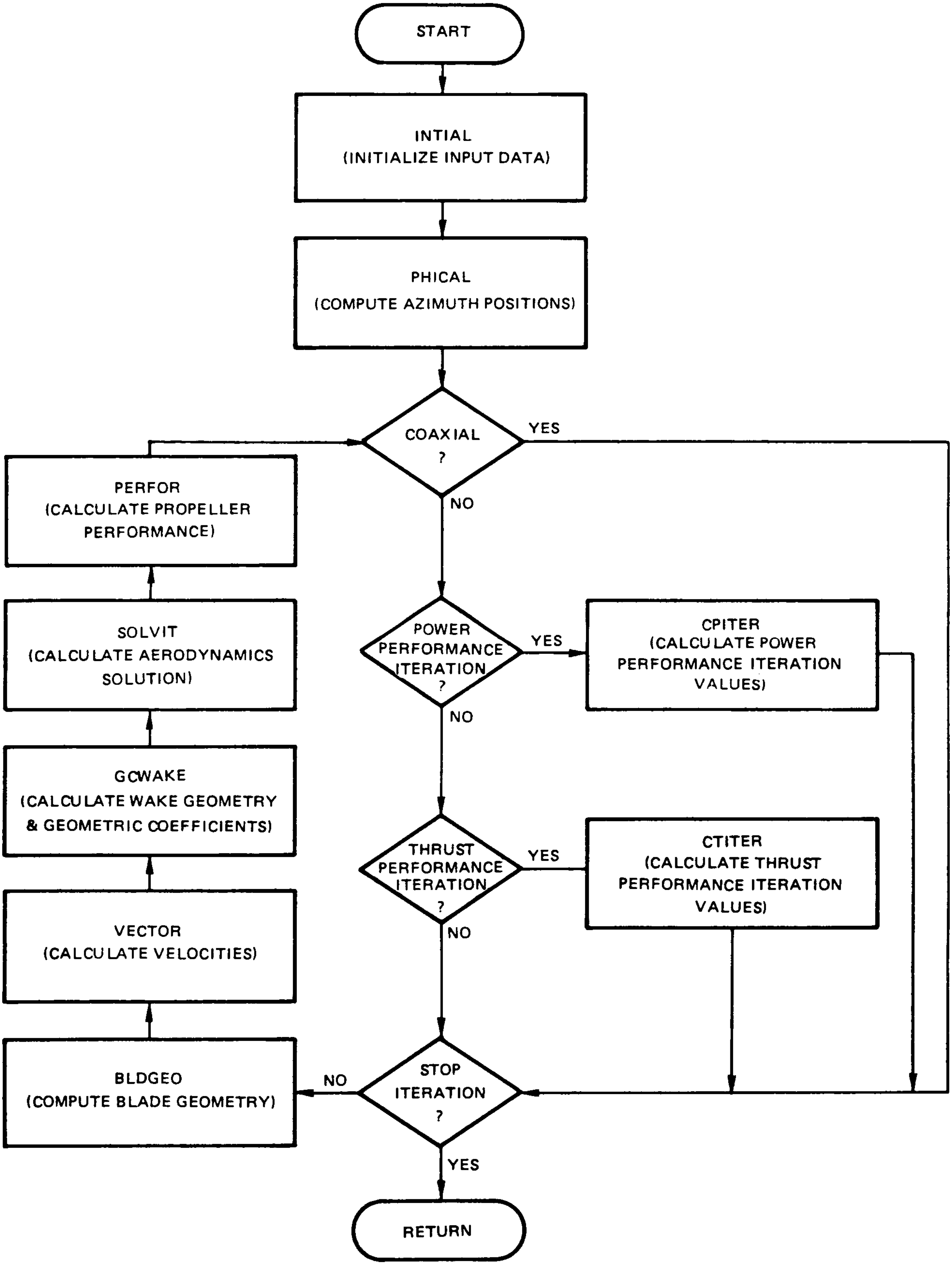



**Figure 13. Flow Diagram of Subroutine PROP**

85–4–90–32

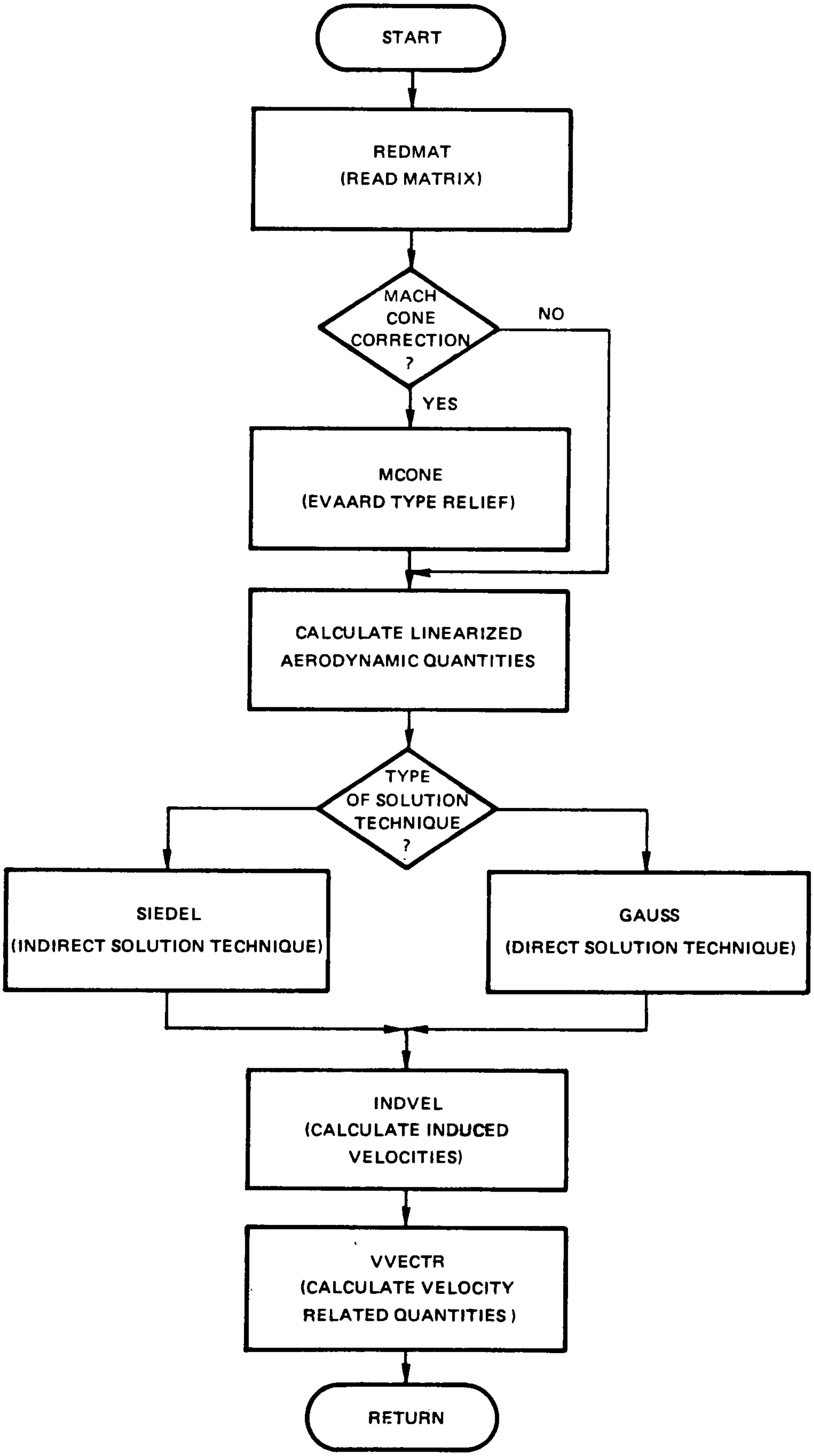



**Figure 14. Flow Diagram of Subroutine SOLVEL**

85–4–90–33

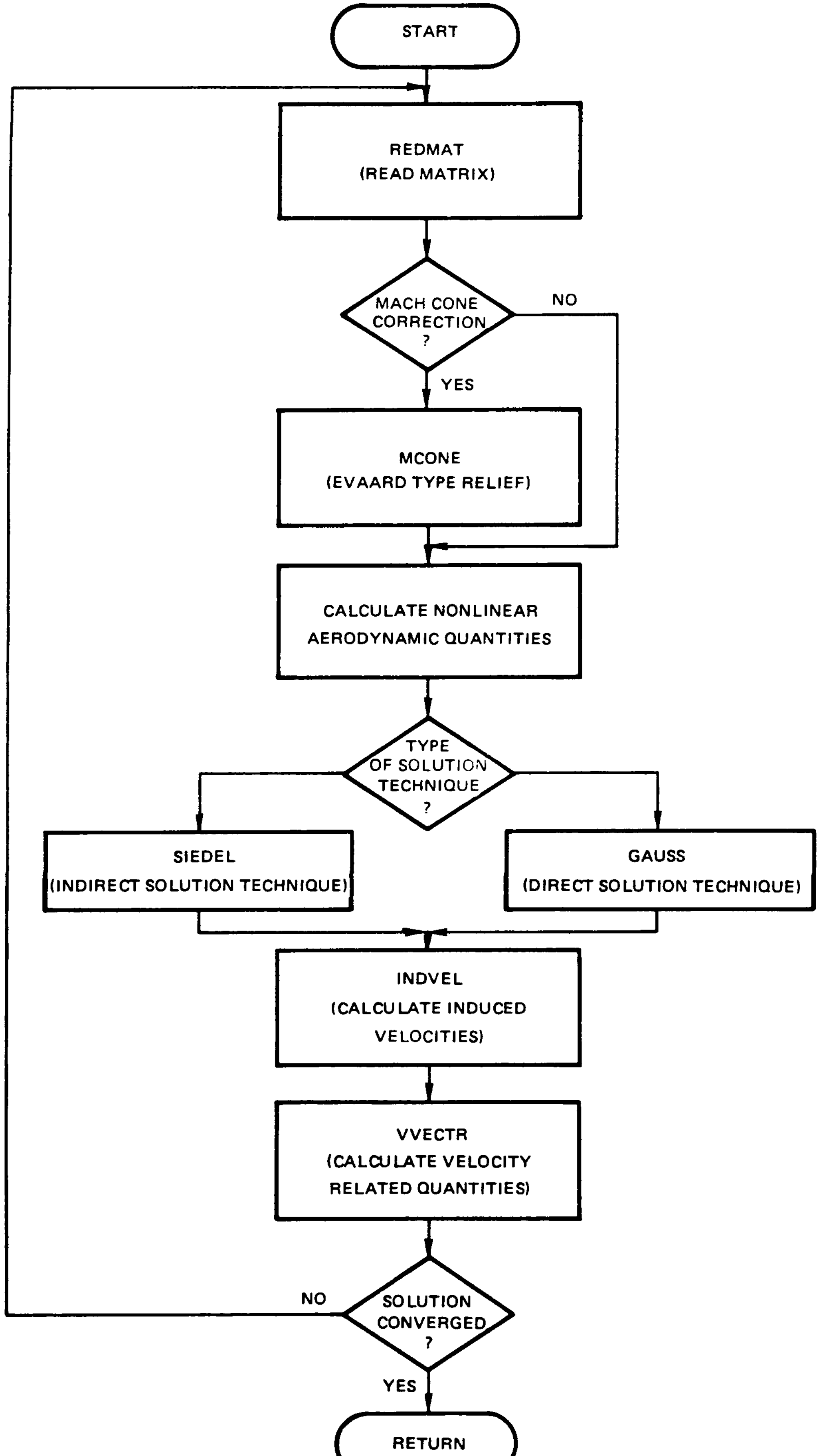



**Figure 15. Flow Diagram of Subroutine SOLVEN**

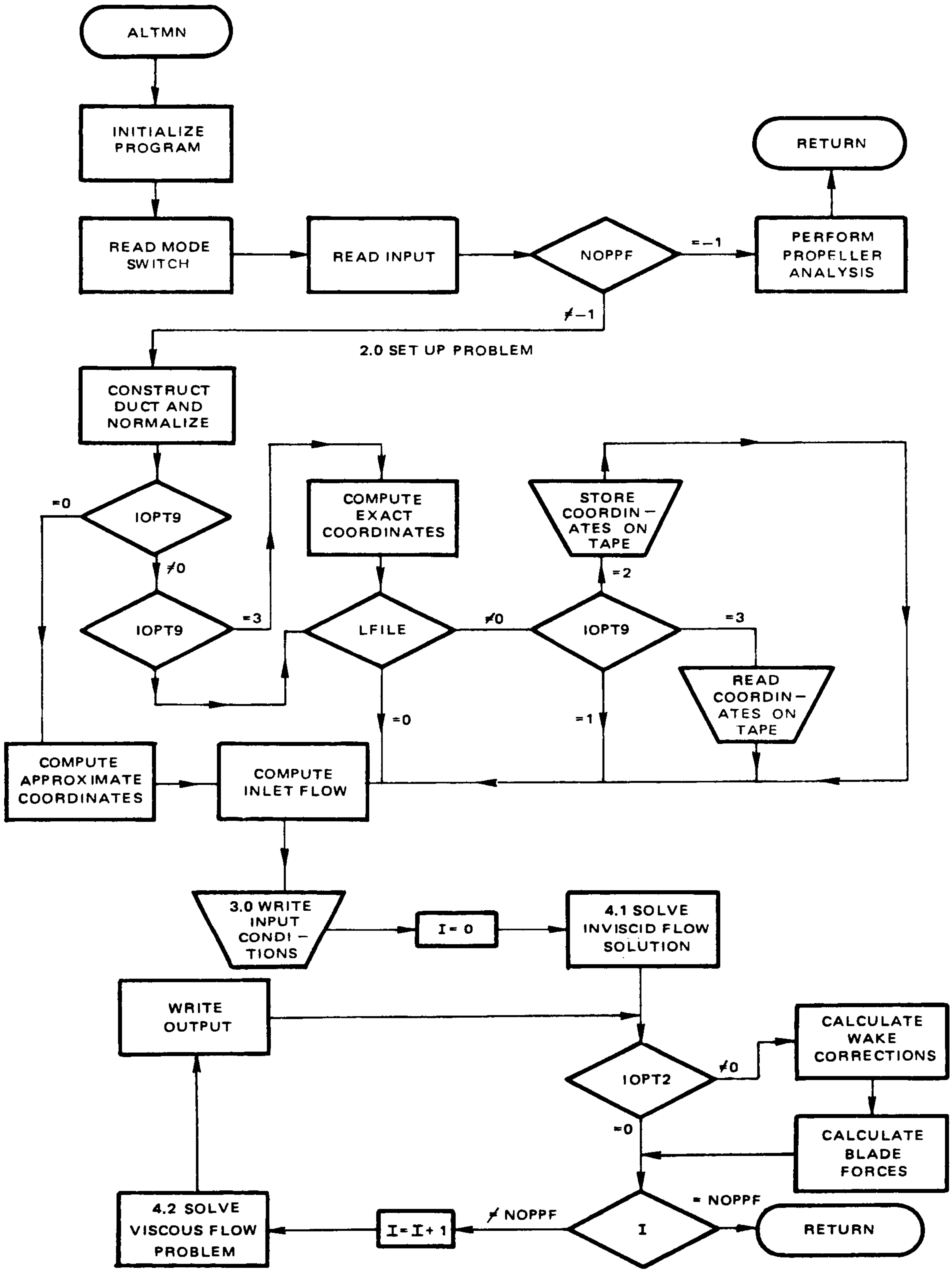
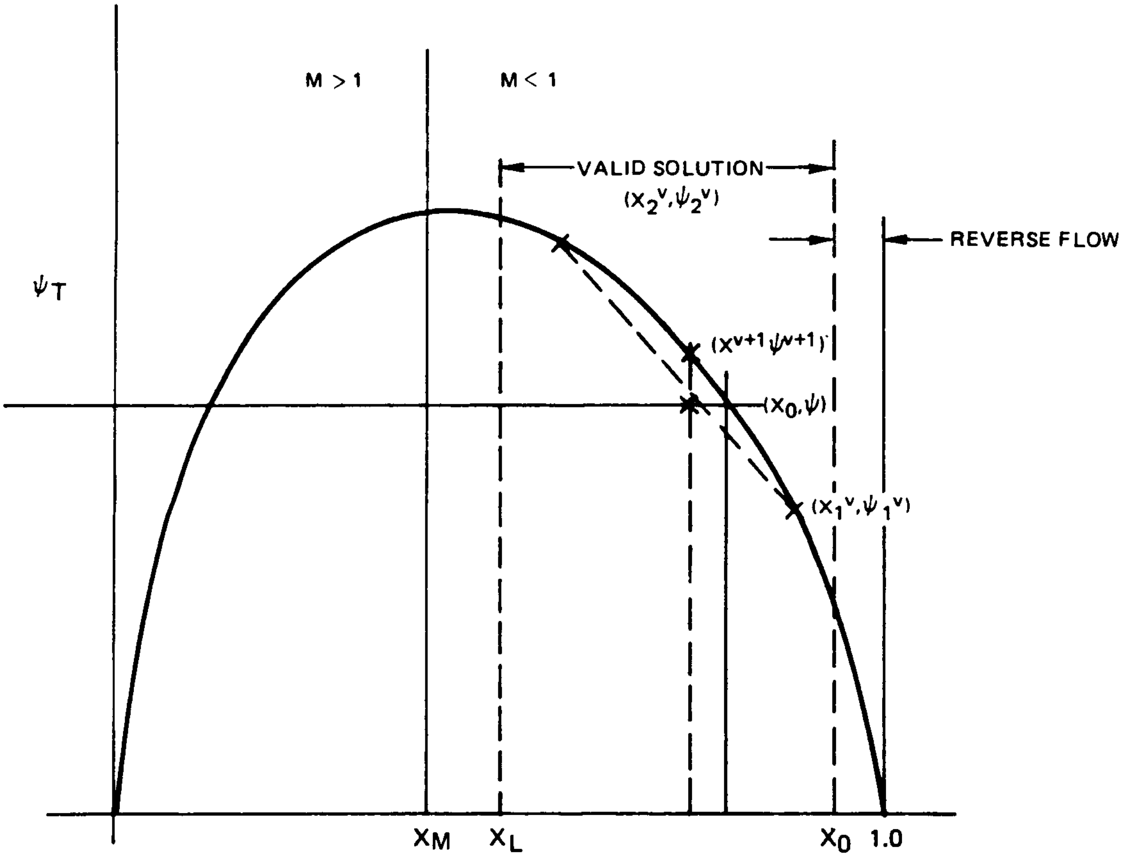



**Figure 16. Flow Chart for ALTMN**

85–4–90–35




$$X^{v+1} = X_1^v + \frac{\psi - \psi_1^v}{\psi_2^v - \psi_1^v} (X_2^v - X_1^v)$$

$$\text{IF}(\psi^{v+1} > \psi) \qquad X_2^v = X^v;\ \psi_2^v = \psi$$

$$\text{IF}(\psi^{v+1} < \psi) \qquad X_1^v = X^v;\ \psi_1^v = \psi$$

**Figure 17. Iteration Procedure**

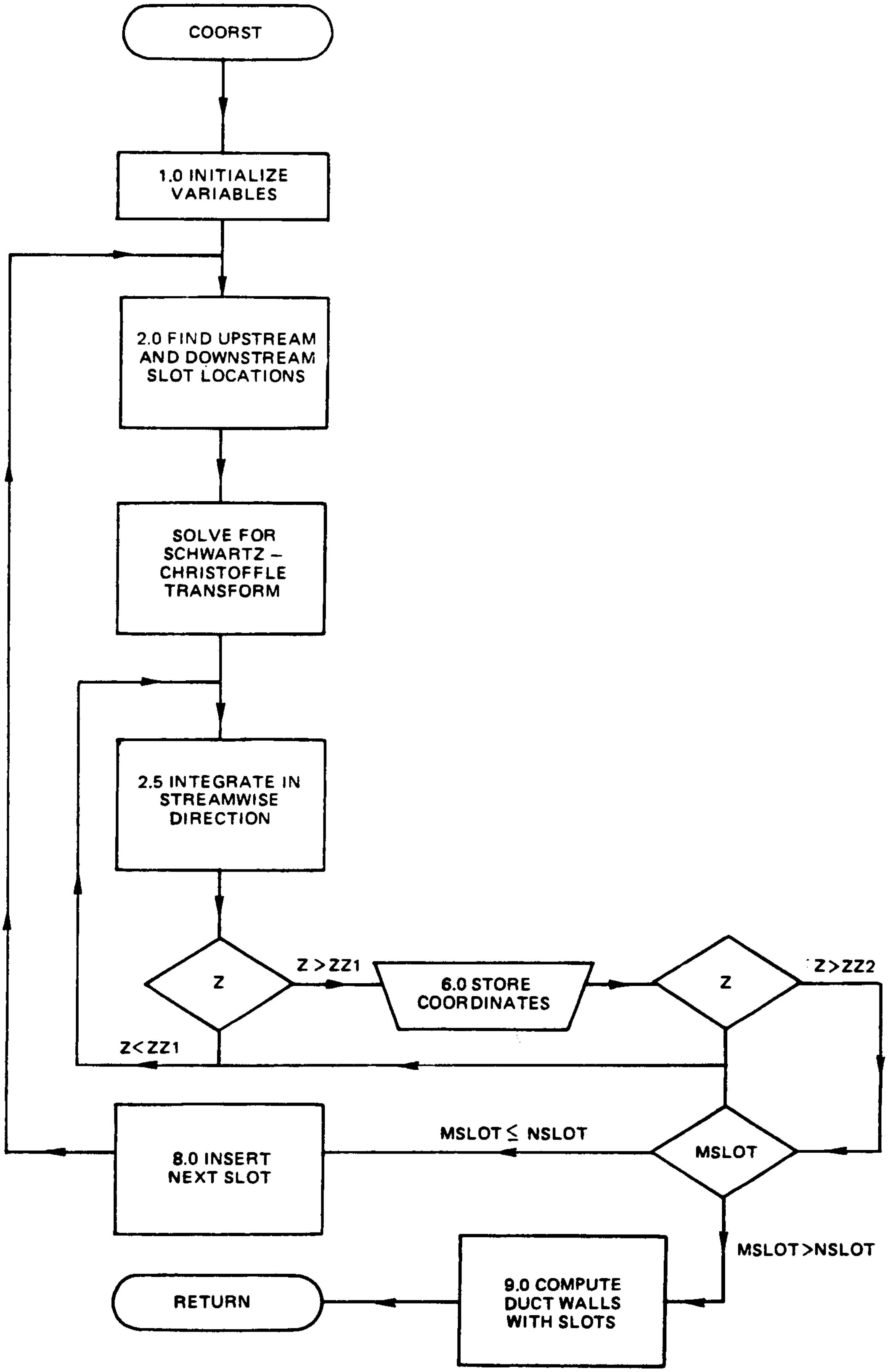



**Figure 18. Flow Chart for Subroutine COORST**

85–4–90–37

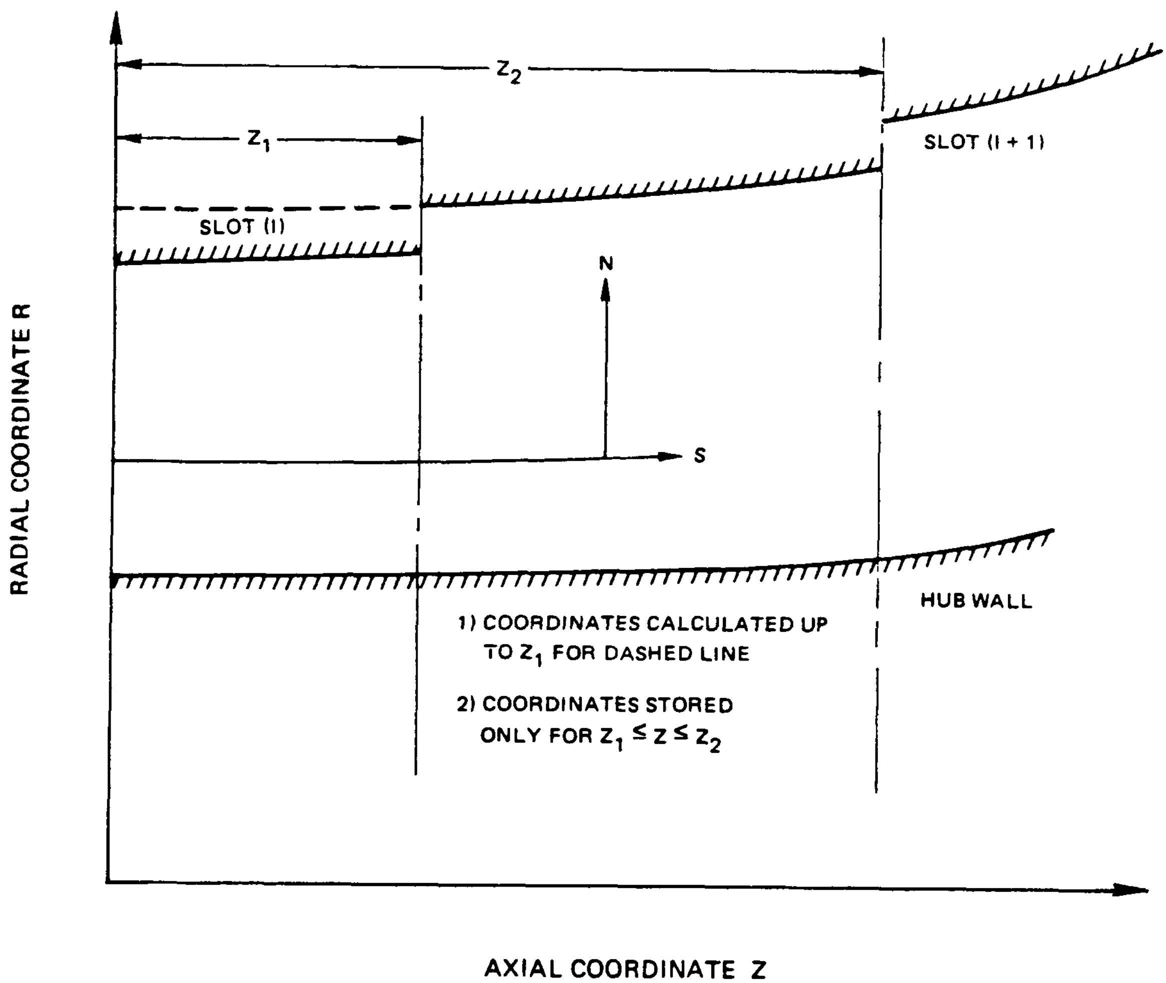



**Figure 19. Calculating Ducts with Slots**

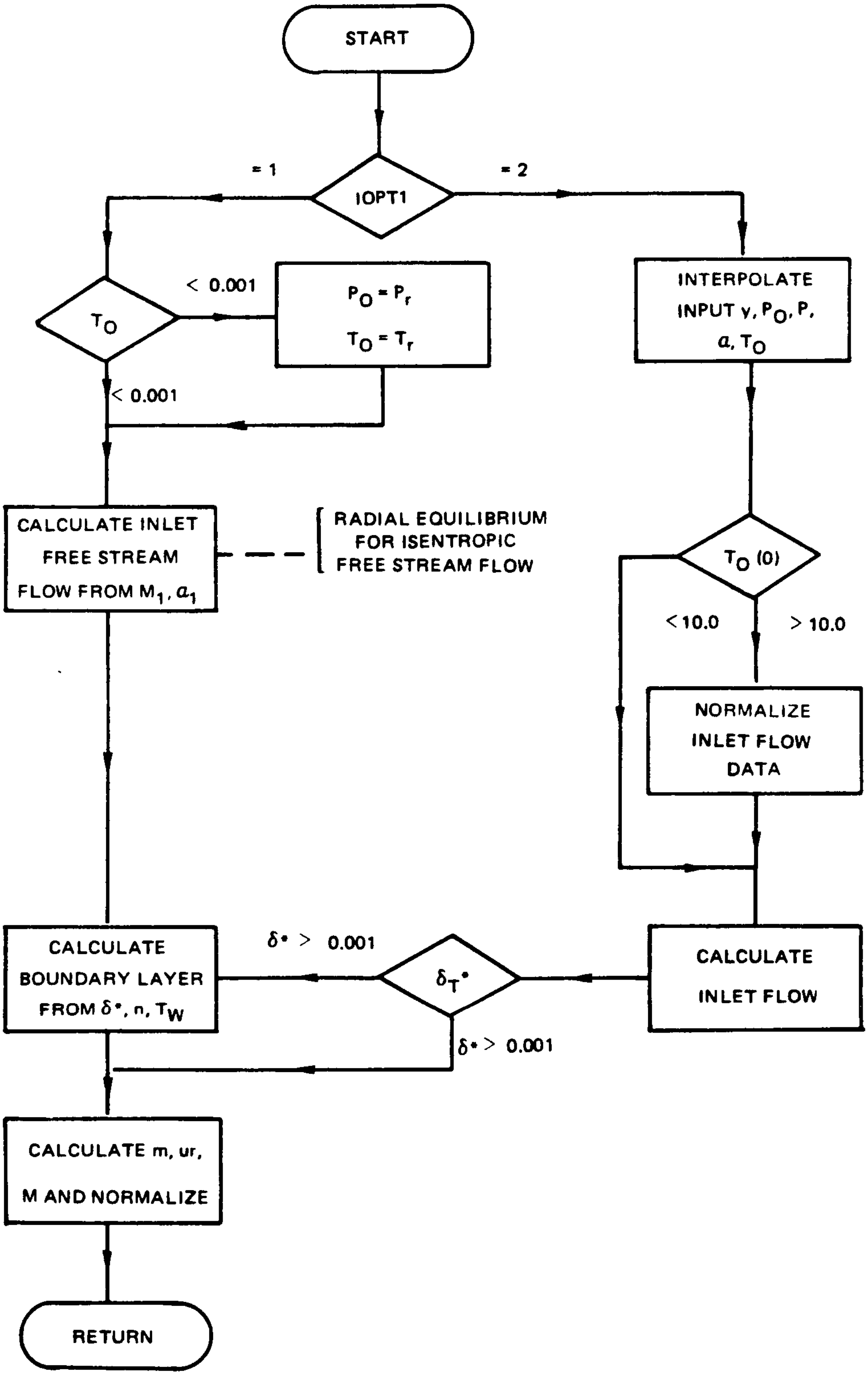



Figure 20. Flow Chart for Subroutine Flowin



85—4—90—39

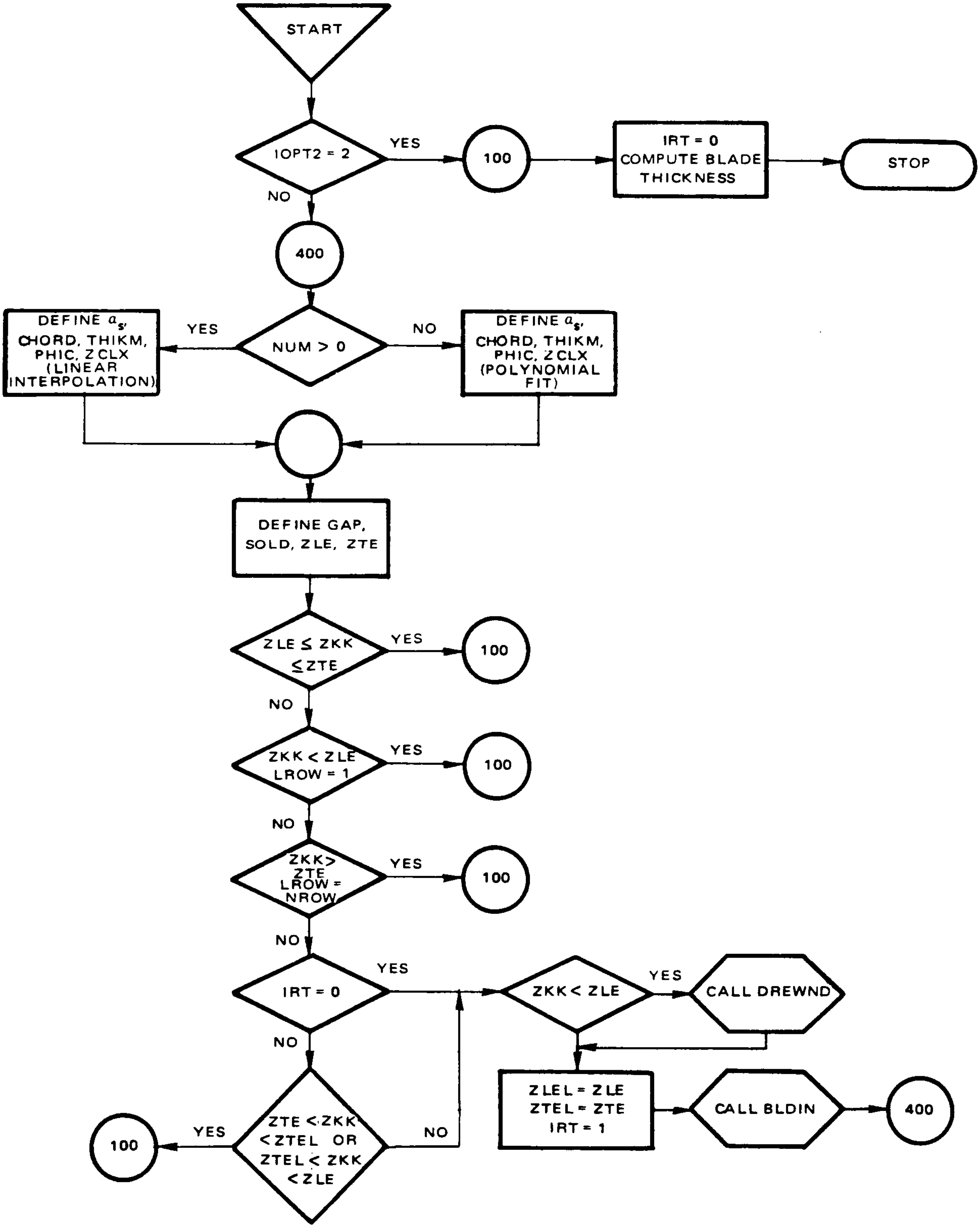



**Figure 21. Flow Chart for GBlade**



85–4–90–40

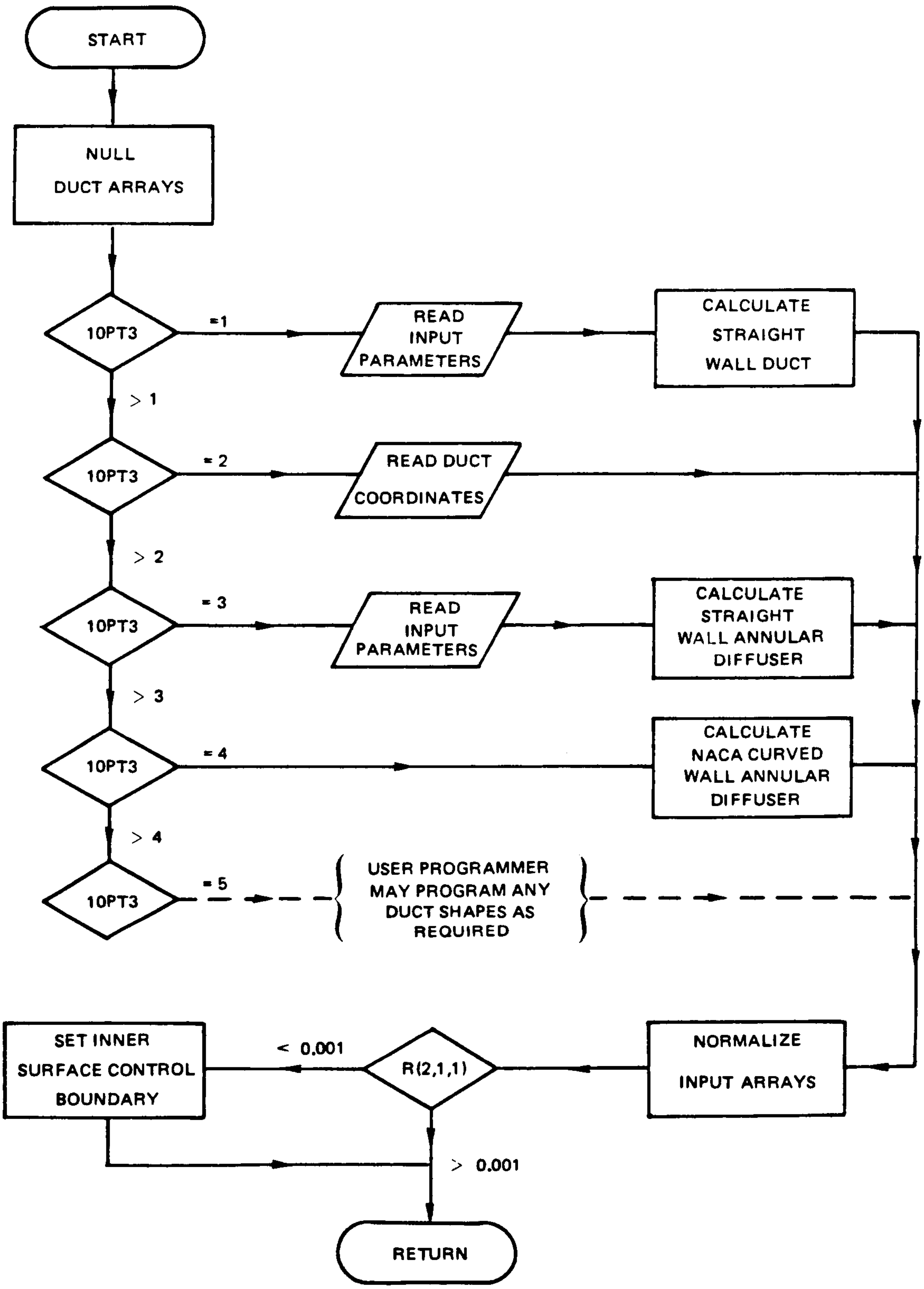



**Figure 22. Flow Chart for Subroutine GDuct**



85—4—90—41

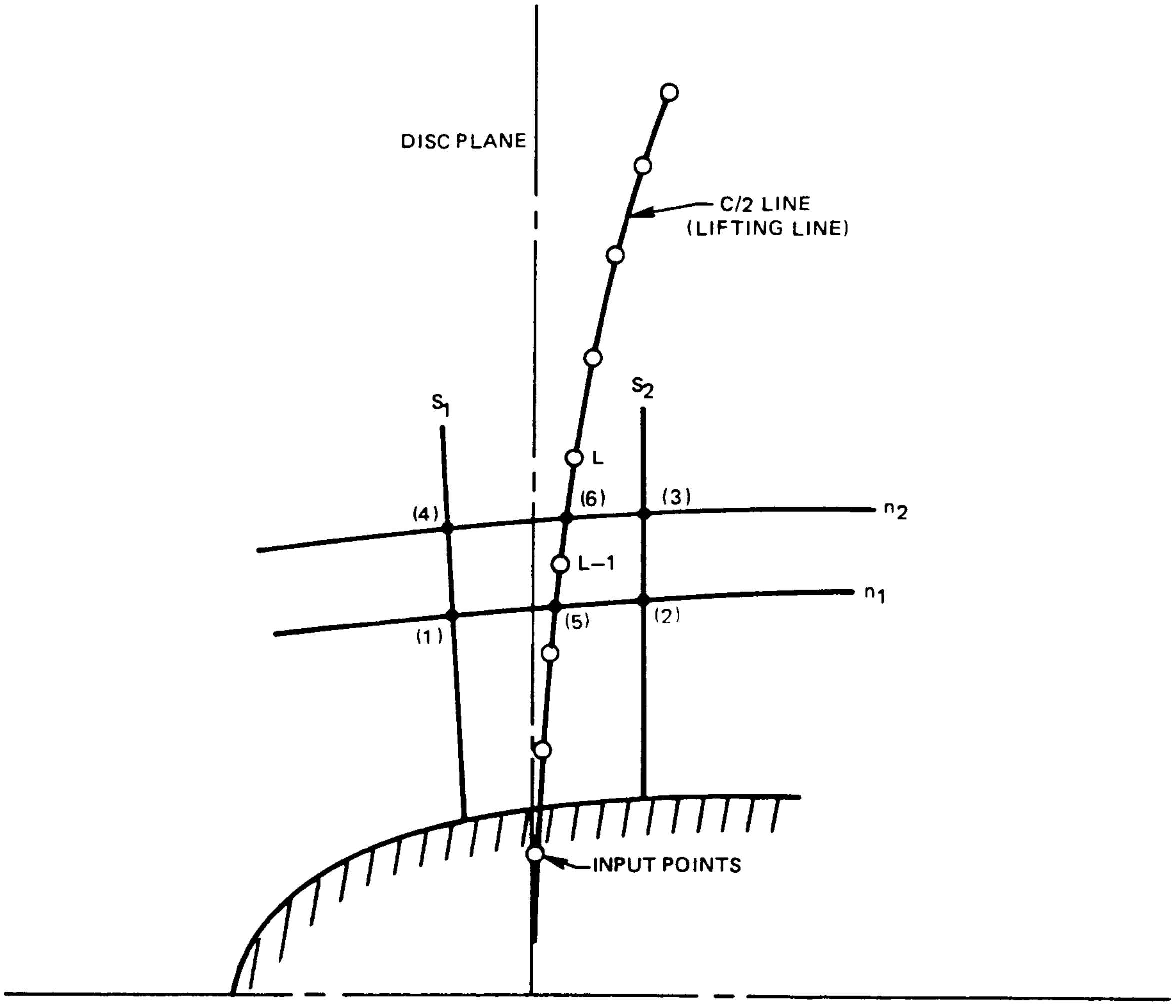



**Figure 23. Locating Lifting Line in Steamline Coordinates**

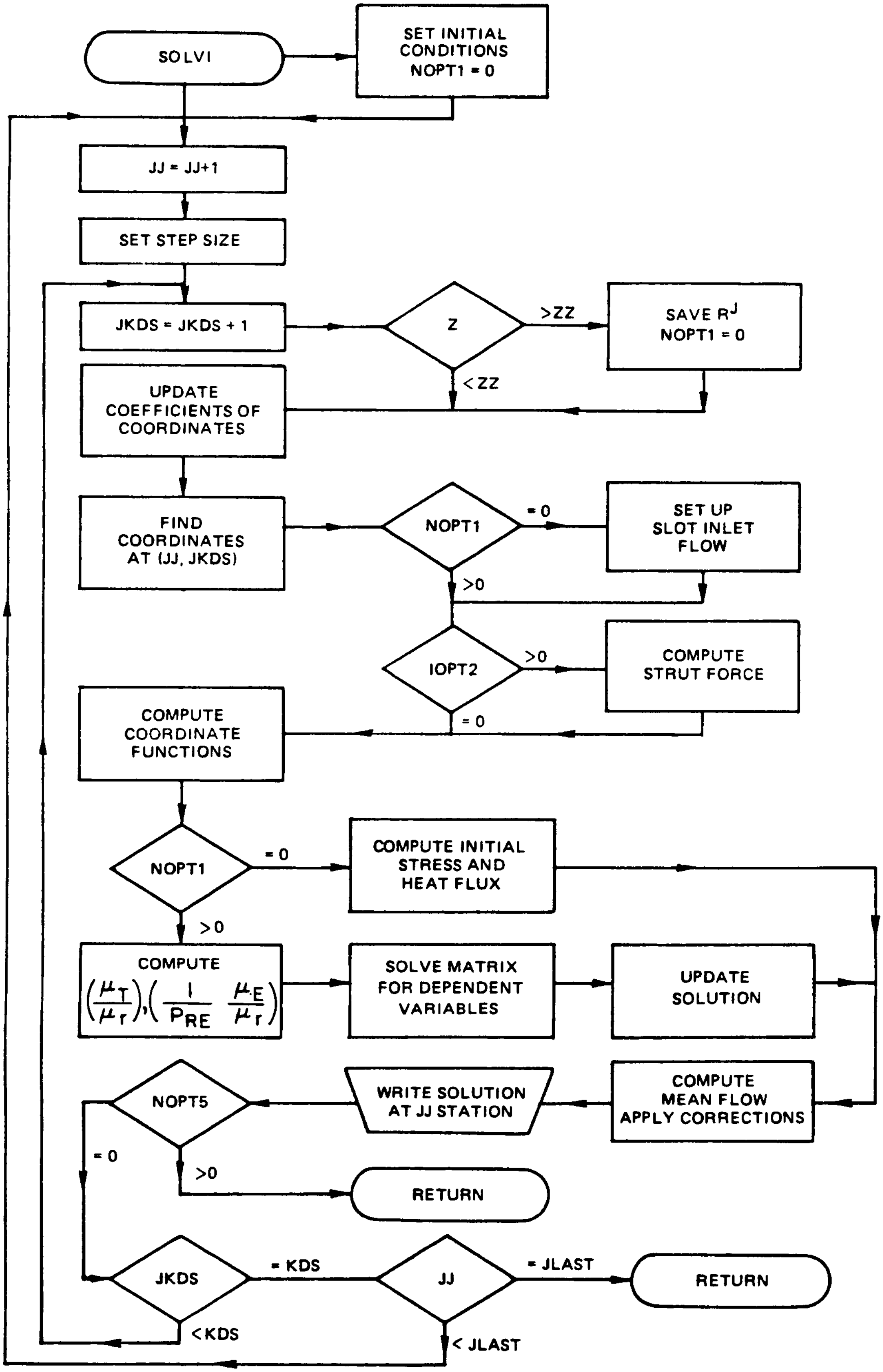



**Figure 24. Flow Diagram for Subroutine SOLVI**

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15. Supplementary Notes

Project Managers, Lawrence J. Bober and Christopher E. Hughes, Propulsion Systems Division, NASA Lewis Research Center.

16. Abstract

A user's manual for the computer program developed for the prediction of propeller-nacelle performance reported in "An Analysis for High Speed Propeller-Nacelle Aerodynamic Performance Prediction. Volume I—Theory and Application" is presented. The manual describes the computer program mode of operation requirements, input structure, input data requirements and the program output. In addition, it provides the user with documentation of the internal program structure and software used in the computer program as it relates to the theory presented in Volume I. Sample input data setups are provided along with selected printout of the program output for one of the sample setups.

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